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FFG-7 Ship Motion and Airwake Trial: Part II - Removal of Ship Motion Effects from Measured Airwake Data

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DEPARTMENT OF DEFENCE
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ABSTRACT

A trial to measure ship motion and airwake has been carried out aboard an 'Adelaide' class FFG-7 frigate. This document outlines a process that has been developed whereby the ship attitudes, velocities, and displacement, including initial conditions, may be determined from limited measured data. The use of software developed to remove the resulting ship motion from the measured airwake data is also shown.

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EXECUTIVE SUMMARY

A helicopter/ship computer model has been developed to simulate the complex interactions in the dynamic interface between ship and helicopter, in particular between the 'Adelaide' class FFG-7 frigate and Sikorsky S-70B-2, a combination used by the Royal Australian Navy (RAN). The model includes helicopter flight dynamics and engine dynamics, undercarriage dynamics, the RAST (Recovery Assist, Secure, and Traverse) system, ship motion, and a representation of the airwake. The original ship airwake model used in the simulation code has been studied and found to have marked differences between the calculated and measured airwake velocities, when applied to an FFG-7 frigate.

From 18 to 21 September 1989, a trial was undertaken aboard HMAS Darwin, an 'Adelaide' class frigate, fitted with stabilisers and RAST equipment. The objective of the trial was to measure the ship motion and airwake over the flight deck for a variety of wind-over-deck velocities for use as a data base in the helicopter/ship simulation code.

Given limited measured data with no direct measurement of ship roll and pitch attitude, a procedure has been developed for determining ship motion and removing this effect from measured airwake data. The same technique for determining ship motion may be used in future trials, with a notable difference being that if attitude is measured directly, then it is not necessary to use derived mean values as an approximation. The accuracy of the calculated ship velocity may be improved by lengthening the data recording time and by including extra velocity and displacement information from a satellite navigation system.

It has been shown that the mean of the measured airwake is approximately the same as the mean of the airwake when corrected for motion effects. With hindsight, this is an inevitable result, as the mean angular rates must approach zero and the ship is assumed to have mean linear velocities approaching zero in the motion analysis. For the applications of using the measured data as a mean flow data base for the helicopter/ship model, or for comparison with wind tunnel results, the procedure for removing motion effects from the airwake is therefore not warranted. However, it should be noted that the technique for determining ship motion developed here has also been applied to determining the motion of a 'Perth' class DDG destroyer and for calculating the position of the flight deck of HMAS Jervis Bay during a Black Hawk First of Class Flight Trial.

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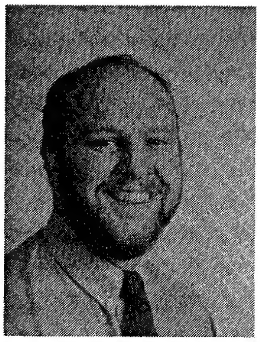

Ashley Arney graduated from the University of Sydney in 1981, having obtained an Aeronautical Engineering Degree, with honours. Since commencing employment at the then Aeronautical Research Laboratory in 1982, he has been involved with the mathematical modelling of the performance and flight dynamics of a wide range of helicopters. He has also obtained extensive experience in trials, data processing, and the use of such data for development of the appropriate mathematical model. More recently he has been involved in modelling the helicopter/ship dynamic interface, and gathering data for development purposes.

CONTENTS

NOMENCLATURE

U, V, W	Ship linear velocity components in ship body axes
$U_{mean}, V_{mean}, W_{mean}$	Mean ship linear velocity components in ship body axes
V_{port}, Ψ_{port}	Magnitude and direction of airwake measured by port cup anemometer
V_{ref}, Ψ_{ref}	Magnitude and direction of airwake measured by aerovane anemometer
V_{ship}, Ψ_{ship}	Magnitude and direction of airwake measured by ship anemometer
V_{stbd}, Ψ_{stbd}	Magnitude and direction of airwake measured by starboard cup anemometer
X, Y, Z	Displacement of ship in earth axes
a'_x, a'_y, a'_z	Accelerometer measurements corrected for offset from centre of ship motion and g effects
a_x, a_y, a_z	Inertial acceleration components in ship body axes
g	Gravitational acceleration (32.17 ft/s^2)
p, q, r	Angular velocity components in ship body axes (roll, pitch, and yaw)
u, v, w	Airwake velocity components corrected for ship motion in ship-carried vertical axes
u_c, v_c, w_c	Airwake velocity components corrected for ship motion in ship body axes
u_m, v_m, w_m	Measured airwake velocity components in ship body axes
x, y, z	Linear displacement components of the accelerometers from centre of ship motion in ship body axes
$x_{base}, y_{base}, z_{base}$	Linear displacement components of mobile anemometer mast base, cup and aerovane anemometers from centre of ship motion in ship body axes
x_{lat}, x_{vert}	Longitudinal displacement of lateral and vertical Gill anemometers from base of mobile anemometer mast in ship body axes
z_{long}, z_{lat}	Vertical displacement of longitudinal and lateral Gill anemometers from base of mobile anemometer mast in ship body axes
$\Delta x_{lat}, \Delta x_{vert}$	Longitudinal displacement of lateral and vertical Gill anemometers from centre of ship motion in ship body axes
$\Delta y_{long}, \Delta y_{vert}$	Lateral displacement of longitudinal and vertical Gill anemometers from centre of ship motion in ship body axes
$\Delta z_{long}, \Delta z_{lat}$	Vertical displacement of longitudinal and lateral Gill anemometers from centre of ship motion in ship body axes
ϕ, θ, ψ	Euler angles (roll, pitch, and yaw)
ϕ_m, θ_m	'Attitudes' derived from accelerometer measurements (roll and pitch)

Additional Subscripts

B	Ship body axes
E	Earth axes
b	Instrument bias (offset) error
m	Measurement
o	Initial condition

1. INTRODUCTION

In 1987, the Defence Science and Technology Organisation (DSTO) obtained a helicopter/ship computer simulation model from the US Naval Air Warfare Center (NAWC) Aircraft Division (previously known as the Naval Air Test Center). The code was obtained under the auspices of The Technical Cooperation Program (TTCP). The model can be used to simulate the complex interactions in the dynamic interface between ship and helicopter, in particular between the 'Adelaide' class FFG-7 frigate and Sikorsky S-70B-2, a combination used by the Royal Australian Navy (RAN). The model includes helicopter flight dynamics and engine dynamics, undercarriage dynamics, the RAST (Recovery Assist, Secure, and Traverse) system, ship motion, and a representation of the airwake (Ref. 1). The model has been substantially modified from its original state and already has been used to assess a number of operational problems for the RAN (Ref. 2). Its main use is expected to be assisting the RAN with developing safe operating envelopes for helicopters operating from ships (Ref. 3).

The original ship airwake model used in the simulation code has been studied by Erm (Ref. 4) and found to have marked differences between the calculated and measured airwake velocities when applied to an FFG-7 frigate. These differences are attributed to the origins and subsequent development of the model, in which measurements based on different class ships were used, with arbitrary changes then made to improve the accuracy of a real-time simulator.

From 18 to 21 September 1989, a trial was undertaken aboard HMAS Darwin, an 'Adelaide' class frigate, fitted with stabilisers and RAST equipment. The objective of the trial was to measure the ship motion and airwake over the flight deck for a variety of wind-over-deck velocities (the trials instructions are detailed in Ref. 5) for use as a data base in the acquired simulation code. The instrumentation package, including motion sensors and anemometers, is reported in Ref. 6 and the data were recorded using a data acquisition system (Ref. 7) developed by Air Operations Division (AOD). Prior to the trial, calibrations were obtained for (a) anemometers in the AOD low-speed wind tunnel, (b) angular rates on a rate table, and (c) attitudes on a tilt table. Just before sailing, measurements were taken while the ship was alongside. The purpose of this was to provide procedural practice for the trials team and obtain data for the zero ship motion case as a baseline when investigating effects of ship motion for the 'at sea' cases.

The results of the trial to measure ship motion and airwake are documented in three parts. Part I (Ref. 9) gives a brief description of the scope of the trial and details of the data gathering aboard ship, and demonstrates the use of data reduction software developed to obtain processed data in imperial units from the raw measured data. This report is Part II and Part III (Ref. 10) presents the airwake mean flow and turbulence levels over the flight deck of the FFG-7.

This report outlines a process that has been developed whereby the ship attitudes, velocities, and displacement, including initial conditions, may be determined from limited data through parameter estimation. The use of software developed to remove the calculated ship motion from the measured airwake data, then transform it from ship body axes to ship-carried vertical axes, is also described. Results for calculating the ship motion are given along with a comparison of airwake data in ship body axes with airwake data in ship-carried vertical axes that have the motion-induced component removed.

Imperial units are adopted in this report because (a) they are used exclusively by research workers in the US with whom AOD is collaborating and (b) both the helicopter and ship referred to are built in the US to imperial unit specifications.

2. MEASUREMENTS ACQUIRED DURING TRIAL

The airwake over the flight deck was measured using a mobile anemometer mast measuring over 30 feet in height, that was placed at thirteen positions on the flight deck while the officer

of the watch maintained a nominally constant relative wind over deck condition. At each of the thirteen positions, a 90 second recording run was made. The flight deck is situated at the stern of the FFG-7, as shown in Fig. 1, and the mobile airwake mast layout and positions on the flight deck are shown in Fig. 2. For more detailed information on the instrumentation and methods used in acquiring the data, see Ref. 9.

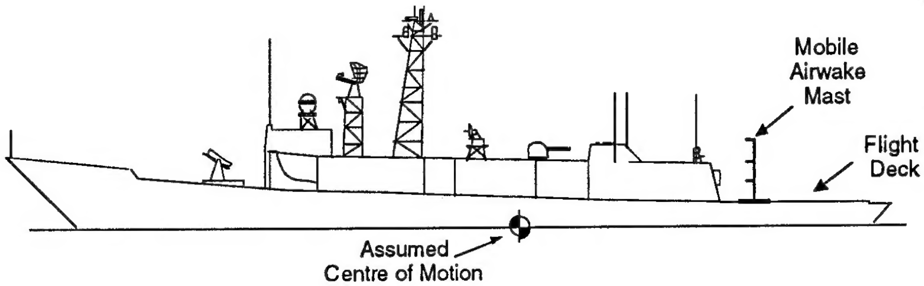

Figure 1. Flight Deck Location

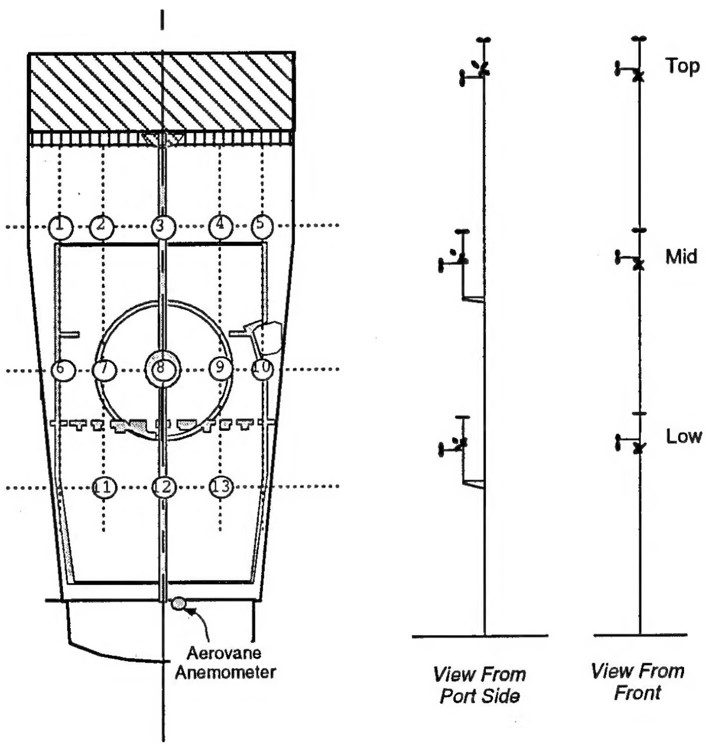

Figure 2. Mobile Mast Layout and Deck Positions

It was thought that the height of the mast above the ship centre of motion was such that velocity induced by the ship motion would be significant. This induced velocity must be removed from the measured data and the resulting airwake velocity data transformed from ship body axes (as measured) to ship-carried vertical axes to give the airwake velocity that would be seen by an object in ship-carried vertical axes over the flight deck (such as a helicopter). Therefore the ship linear velocities, angular rates, and attitudes must be known.

The quantities measured by the ship motion platform included the three acceleration components (a_{x_m}, a_{y_m}, a_{z_m}) and roll, pitch, and yaw rates (p_m, q_m, r_m). Two additional quantities recorded from the ship instrumentation were ship heading (yaw attitude) and ship

speed. It should be noted that the ship speed is measured using a device which would tend to average the actual longitudinal velocity component. As reported in Ref. 9, no direct measurements of the pitch and roll attitudes were made, although some indication of the average attitudes may be obtained from the accelerometer readings, as discussed in Section 3.2.

Thus to determine the ship velocity components and attitudes, the measurements available are

- three acceleration components
- three angular rates
- average longitudinal velocity
- yaw attitude

Since the ship was not at a known trimmed condition when recording of data commenced, initial conditions are unknown. By using the parameter estimation program *Compat* (Section 3), the ship attitudes, velocities, and displacements, including the initial conditions, may be determined after first making a few reasonable assumptions as discussed in Section 3.2.

The parameter estimation program *Compat* may also be used to check measured data against expected values (as determined from the kinematic equations of motion) to determine bias (drift) in instrumentation.

Data reduction of the measurements obtained from the trial has taken place in two distinct phases. Phase 1 involved deriving the ship velocity components and attitudes from the ship motion platform instrumentation using program *Compat*, and Phase 2 involved correction of the anemometer measurements and removal of the ship motion components from the measured airwake velocities using program *AWSM*.

3. CALCULATING SHIP MOTION

To determine ship motion from the limited data measured aboard ship, a compatibility checking technique has been developed using the program *Compat* (Refs 11 and 12). Because of the intense numerical calculations involved, this program is run on a RISC 6000 machine. The technique developed here has also been applied to determining the motion of a 'Perth' class DDG destroyer (Ref. 13) and for calculating the position of the flight deck of the training ship HMAS Jervis Bay during a Black Hawk First of Class Flight Trial.

The axes systems used in the motion analysis are first defined in Figure 3. Note that at time t = 0, the origins of the earth axes and ship body axes are coincident, but the initial euler roll and pitch angles may be non-zero.

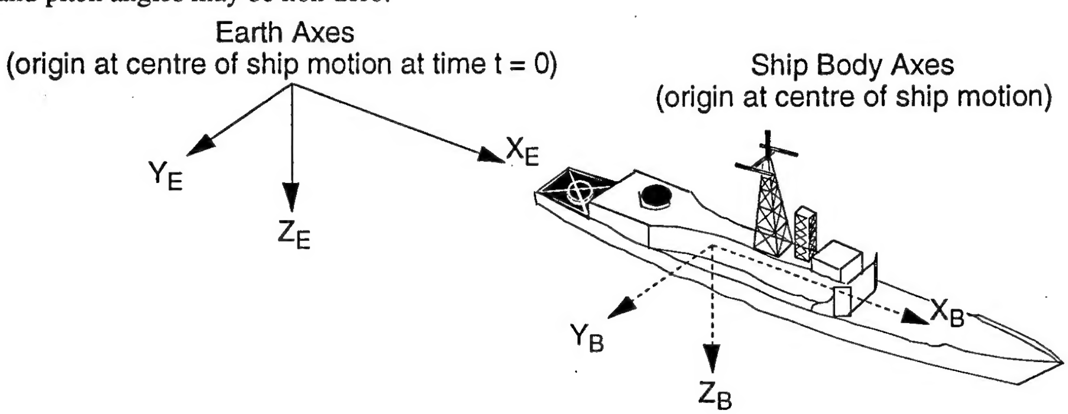

Figure 3. Axes Systems

For this particular trial, program *Compat* is first used to determine offset errors in the instrumentation then calculate motion data, namely attitudes and velocities, from the limited

measured data. This section describes the unique subroutines required for determining ship motion, and the procedure to be followed to obtain the required output.

3.1 Program *Compat*

The compatibility checking program *Compat* has been modified from its original form to allow it to run on personal computers (PCs) with limited memory. The resulting code has been rewritten in a structured way so that the code is much easier to understand and modify, but in the process has lost the ability to estimate time-shifts in flight data.[1] However, this version of the code is more easily transported to different machines.

In simple terms, *Compat* takes the rigid body kinematic equations of motion in differential form, integrates them, and then compares the results with measured data. In an iterative process, parameters (that in this case are instrumentation offset errors) are then adjusted to obtain a better match. If the measured data contained no offset errors then there would be no difference between the measured response and the predicted response from the integrated equations of motion. For the ship motion application considered here, the process typically requires 25 iterations until convergence occurs, at which point the instrumentation errors and ship motion data are output. The optimisation procedure used in *Compat* is outlined in Figure 4.

For the ship motion application, the control inputs are taken to be the measured accelerations, angular rates, and angular accelerations. The experiment consists of the assumed velocities and attitudes resulting from these inputs (see Section 3.2), and the mathematical model is the kinematic equations of motion with allowances incorporated for instrumentation offset errors.

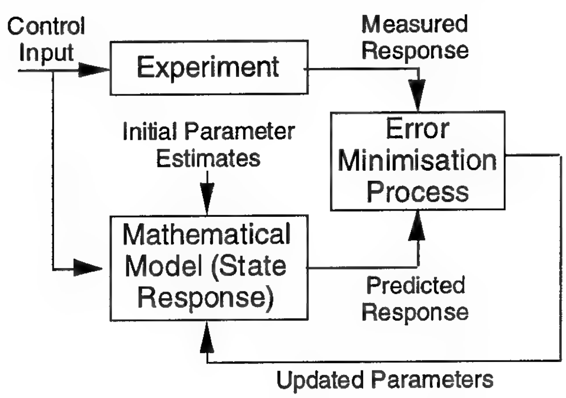

Figure 4. Parameter Estimation Procedure Used in Program *Compat*

Compat requires two data files as input. The `COMDAT.xxx` file controls operation of the program by defining which parameters are to be determined, how many controls, states, and measurements are involved, and a number of other parameters, defined in Appendix A. For the ship motion analysis, a two-stage method is required using two `COMDAT.xxx` files in two separate runs (see Section 3.3), which are also given in Appendix A. The second data file required by *Compat* (`xxxxxxxx_Out`) contains a time history of the control inputs and measured response data (see Section 3.2).

Three output files are created by *Compat*. They are `COMOUT.FFG`, `THIST.DAT` and `var.dat`. File `COMOUT.FFG` contains run-time information, most details of which will not be discussed here. File `THIST.DAT` contains the measured and observed responses (calculated in `Resp.f`, see below) in the form of time histories. File `var.dat` contains the measured ship longitudinal velocity, the calculated states, and the angular rates corrected for instrument bias errors. Figure 5 shows the program modules and input and output files

[1] The time-shift capability was removed because the way it was originally implemented was too memory intensive for a PC. It is intended to reintroduce the time-shift capability at a later date.

and Table 1 summarises the contents of each data file and module that is discussed further below.

The program itself has three problem-specific subroutines. These subroutines are kept as separate modules (called `Deriv.f`, `Init.f`, and `Resp.f`) and are given in Appendix B, along with the executable file *link*, which compiles and links the required modules to create *Compat*. Subroutine `Deriv.f` contains the derivative equations of motion and the instrumentation error models, `Init.f` contains the initial conditions, and `Resp.f` contains the calculated response. The contents of these subroutines are discussed further below.

For the ship motion, the control inputs (Fig. 4) used are the angular rates and accelerations and the linear accelerations. An error model for the rates and linear accelerations is also included, which allows an offset in the measured data. Equations below are in file `Deriv.f` (Appendix B).

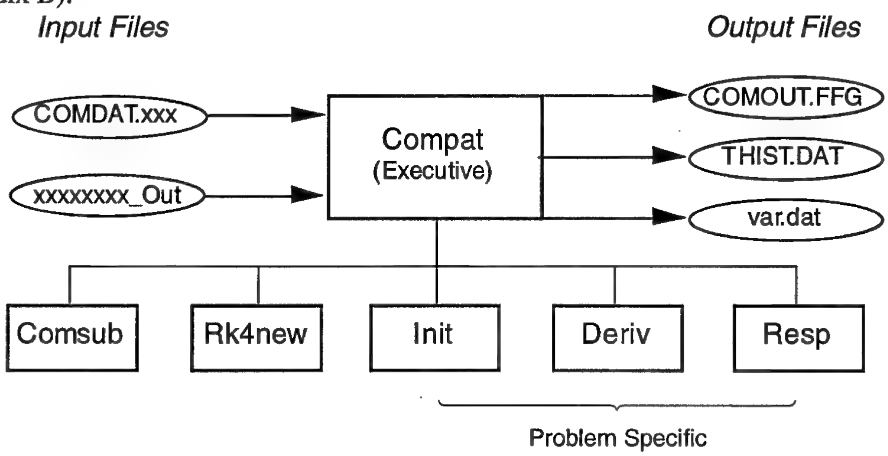

Figure 5. Program Modules and Input and Output Files

Table 1. Summary of Compat Modules and Data Files

Module/File	Description
`COMDAT.xxx`	Program operation inputs
`xxxxxxxx_Out`	Time history of control inputs and measured response data
`COMOUT.FFG`	Run-time information, including estimates of parameters
`THIST.DAT`	Time history of measured data and calculated responses
`var.dat`	Time history of calculated (true) ship motion
`Compat (Executive)`	Executive routine controlling execution of program
`Comsub`	Matrix manipulation routines
`Rk4new`	Integration routine
`Init`	Determines initial conditions
`Deriv`	Derivative equations and error models (math model in Fig. 4)
`Resp`	Predicted responses (calculated ship motion)

The calculated roll, pitch, and yaw rates, p, q, and r, are given by

$$p = p_m + p_b$$
$$q = q_m + q_b$$
$$r = r_m + r_b$$

where control inputs p_m, q_m, r_m are the measured rates and parameters p_b, q_b, r_b are the instrument bias (offset) errors in measured rates.

The calculated linear accelerations along the x, y, and z axes, a_x, a_y, a_z , are given by

$$a_x = a'_x + a_{x_b}$$
$$a_y = a'_y + a_{y_b}$$
$$a_z = a'_z + a_{z_b}$$

where parameters $a_{x_b}, a_{y_b}, a_{z_b}$ are the offset errors in measured linear accelerations and a'_x, a'_y, a'_z are the measured accelerations corrected for accelerometer offset from the centre of ship motion and gravitational effects (Ref. 14), given by

$$a'_x = a_{x_m} + (q^2 + r^2)x - (pq - \dot{r})y - (pr + \dot{q})z - g\sin\theta$$
$$a'_y = a_{y_m} - (pq + \dot{r})x + (p^2 + r^2)y - (qr - \dot{p})z + g\cos\theta\sin\phi$$
$$a'_z = a_{z_m} - (pr - \dot{q})x - (qr + \dot{p})y + (p^2 + q^2)z + g\cos\theta\cos\phi$$

where control inputs $a_{x_m}, a_{y_m}, a_{z_m}$ are the measured linear accelerations, $\dot{p}, \dot{q}, \dot{r}$ are the calculated roll, pitch, and yaw accelerations,[1] and parameters x, y, z are the linear displacements of the accelerometers from the centre of ship motion.

The state variables (referred to as states) defining the system are the Euler angles (ϕ, θ, ψ), linear velocities in ship body axes (U, V, W), and displacements in earth axes (X, Y, Z), which are found by integrating the following standard rigid body kinematic equations of motion (Ref. 14):

$$\dot{\phi} = p + q\sin\phi\tan\theta + r\cos\phi\tan\theta$$
$$\dot{\theta} = q\cos\phi - r\sin\phi$$
$$\dot{\psi} = (q\sin\phi + r\cos\phi)\sec\theta$$
$$\dot{U} = a_x - qW + rV$$
$$\dot{V} = a_y - rU + pW$$
$$\dot{W} = a_z - pV + qU$$
$$\dot{X} = U\cos\theta\cos\psi + V(\sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi) + W(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)$$
$$\dot{Y} = U\cos\theta\sin\psi + V(\sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi) + W(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)$$
$$\dot{Z} = -U\sin\theta + V\cos\theta\sin\phi + W\cos\theta\cos\phi$$

When the data runs were recorded, the initial conditions for many of the states were unknown. File `Init.f` (Appendix B) gives the user several options for determining initial conditions. These include a least squares fit to the first few data points, updating the measured value using error models defined in `Resp.f`, or estimating the initial condition as separate parameters. Since U, V, W, Z, ϕ, and θ were not measured, the only option is to estimate initial conditions. By definition, the initial conditions for X, Y, and ψ are zero.

The observed responses which are compared with measured data are defined in subroutine `Resp.f` (Appendix B) and are generally the integrated values of the state derivatives, with the exception of X and Y. Initially, the measured data for X were assumed to be Ut, and for Y were assumed to have a mean value of zero since no measured data were available for comparison. However, this resulted in parameters which were obviously incorrect. A mechanism was required whereby the derivative equations for $\dot{X}$ and $\dot{Y}$ could still be used to

1 The true angular accelerations, $\dot{p}, \dot{q}$, and $\dot{r}$, are input to the program as control inputs *UU(7)*, *UU(8)*, and *UU(9)* (Appendix B). They are derived from the filtered measured rates (Ref. 9), which are assumed to have only an offset error, and thus are assumed to be true accelerations.

calculate X and Y while avoiding optimising the parameters to match measured and observed responses for X and Y. A solution was to set the observed responses for X and Y equal to the measured data, which were arbitrarily set to zero.

3.2 Preparing Time History Input Data for Program *Compat*

The time history data file (`xxxxxxxx_Out`), which is used as input to *Compat*, must be in the format defined in Table 2.

The parameters measured by the ship motion platform (Ref. 9) included the three acceleration components $(a_{x_m}, a_{y_m}, a_{z_m})$ and roll, pitch, and yaw rates (p_m, q_m, r_m). Two additional parameters recorded from the ship instrumentation were ship heading (ψ_m) and ship speed (U_m). It should be noted that the ship speed is measured using a device which would tend to average the actual longitudinal velocity component.

Table 2. Input Format Required by Compat

Column	Variable	Comments
1	*Time*	
2-4	$a_{x_m}, a_{y_m}, a_{z_m}$	Control Inputs
5-7	p_m, q_m, r_m	Control Inputs
8-10	$\dot{p}, \dot{q}, \dot{r}$	Control Inputs
11-13	U_m, V_m, W_m	Measured Responses
14-16	ϕ_m, θ_m, ψ_m	Measured Responses
17-19	X_m, Y_m, Z_m	Measured Responses

As reported in Ref. 1, no direct measurements of the pitch and roll attitudes were made, although some indication of the mean attitudes may be obtained from the accelerometer readings. For example, in a static condition, if the ship rolled 90°, the lateral accelerometer would read $1g$ (close to 32.2 ft/s²). Thus attitude derived from accelerometer measurements is given by

$$\phi_m = -\arcsin\left(\frac{a_{y_m}}{g}\right)$$

$$\theta_m = \arcsin\left(\frac{a_{x_m}}{g}\right)$$

However, for the dynamic case of ship motion, the accelerometers also sense linear accelerations of the ship due to wave movement. Since the ship is maintaining a steady forward velocity, it may be assumed that the mean acceleration components due to wave movement are zero.[1] Thus the mean values derived from the accelerometers correspond to the mean attitudes, as determined by *Compat*, and so provide additional information necessary for the parameter estimation process to succeed.

Lateral and vertical velocities in body axes (V_m and W_m respectively), and displacement in earth axes (Z_m), were not measured, but the data file for *Compat* must contain values to compare with. If the ship is sailing at a constant speed and heading, then it is reasonable to assume that the mean velocities and vertical displacement over a sufficiently long time period (taken as over 60 s, see Section 5.1) will be effectively zero. Thus by using constant values of zero for V_m , W_m , and Z_m as input, *Compat* will calculate V, W, and Z such that the mean will be zero. Constant values for X_m and Y_m are also used as described in Section 3.1.

---

1 During this trial the sea conditions were relatively benign. If the sea was such that the ship forward velocity was not reasonably steady during the data recording period, then either the recording period would need to be increased or another technique would need to be developed.

In order to create the `xxxxxxxx_Out` input file, which contains both measured data and data derived using the above assumptions, several utility programs (written in Fortran) are available for use on Macintosh computers.

Program *MacTrans* (Ref. 8) is first used to obtain data in imperial units from the data file generated using program *MacShipRefine* (Ref. 9). Appendix C includes a copy of file `MOTION.BLK`, which contains a list of the channels required in the correct order (L1, L2) for use with other utility programs outlined below. Before running *MacTrans*, file `MOTION.BLK` should be renamed to `TRANS.BLK`. An example demonstrating the use of *MacTrans* is shown below for the data file `20091158.DAT` (bold italic type being user inputs and <CR> denoting a carriage-return).

```
[TRANS version date 12-FEB-91]

GO STRAIGHT TO EVENT LOOP?
I/P FILENAME = 20091158
Wind 60 deg, 20 kn - Position 10
File 20091158 (filtered)

I/P FILE RECORDED ON 17-FEB-93   AT 10:11:28

INTEGN INT = 0.0000E+00; RUN CPU TIME =    3 MIN. 24.47 SEC.

TIME FROM 0.0000E+00 TO 8.9500E+01 IN STEPS OF 5.0000E-02

*PRC
PRINTING IN COLUMNS :

BLKS
L1,L2
<CR>
IS O/P TO TTY REQRD : N
*GOE
** RUNNING **
*EXI
```

The resulting data file, 20091158.COL, is then used as input to program *FFGConvert (Attitudes)*. This utility program converts the *MacTrans* column format into the required multi-column form (Table 2), which is also more easily read in by other programs. When running program *FFGConvert (Attitudes)*, a window appears prompting for the name of the *MacTrans* output file (Fig. 6). After selecting the appropriate file, which for this example is 20091158.COL, the output file that is automatically named after the input file, `20091158 (Angles)`, is produced.

Program *KaleidaGraph*[1] is used to read in data file `20091158 (Angles)` and then to plot columns 14 and 15 (ϕ_m and θ_m). The mean attitudes may then be determined using a linear curve-fit. The equation for a linear curve-fit is used, rather than a constant mean value, to allow for a drift in the mean over time. The results for roll and pitch 'attitudes' are shown in Figure 7.

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1 © Abelbeck Software, distributed by Synergy Software (PCS Inc.), 2457 Perkiomen Avenue, Reading, PA 19606, USA.

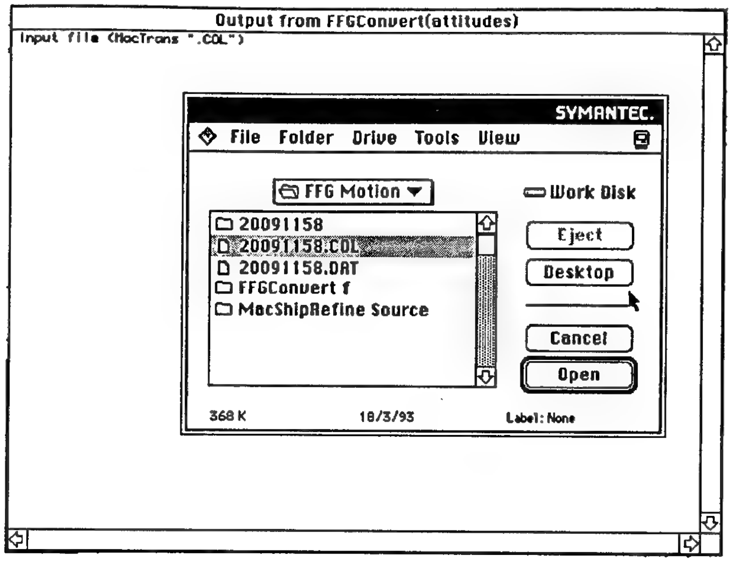


Figure 6. Window For Running *FFGConvert (Attitudes)*

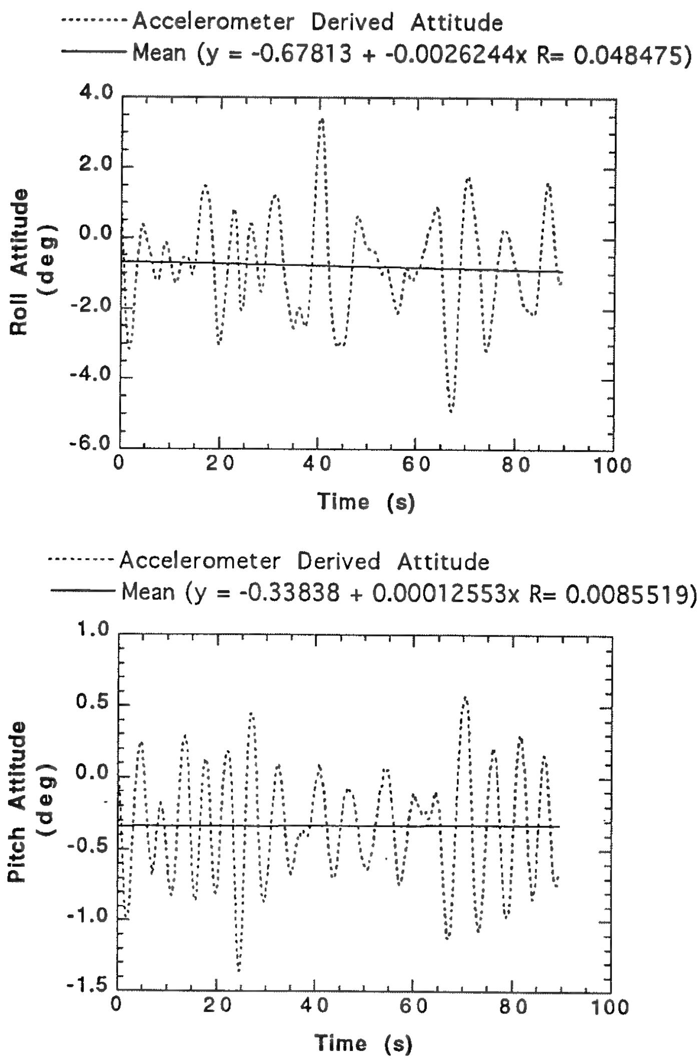


Figure 7. Roll and Pitch 'Attitudes'

Program *FFGConvert(heave)* generates the data file `20091158 Out`, which contains zero values for the lateral and vertical velocity components and vertical displacement, and also calculates values of ϕ and θ according to the linear curve-fits given by *KaleidaGraph*. When running *FFGConvert(heave)*, a window appears (Figure 8) which prompts for the offsets and gradients as determined above.

```
Output from FFGConvert(heave)
Input file (MacTrans ".COL")
Input Attitude Equation Coefficients (deg)

Roll Offset: -.67813
Roll Gradient: -.0026244
Pitch Offset: -.33838
Pitch Gradient: .00012553

STOP
```

Figure 8. Window For Running *FFGConvert(heave)*

3.3 Running *Compat*

Having created the *Compat* input file `20091158 Out` on a Macintosh computer (Section 3.2), the file is transferred to a Risc 6000 machine using ftp in the text mode via program *Versaterm Pro* (© Abelbeck Software). On the Unix based machines, spaces in filenames are converted to underscores; thus file `20091158 Out` becomes`20091158_Out`.

It was determined at an early stage that *Compat* would not always converge if an attempt was made to optimise simultaneously all the parameters required for all the states. Because the equations for the Euler angles are decoupled from the other equations, the parameters associated with the angles are first determined (offset errors in rates and initial conditions of attitudes). The parameters are then set constant for a second run of *Compat* when the parameters associated with the other state variables are found. The parameters are referred to by the designated numbers defined in the input files given in Appendix A. The computer variable names are often slightly different from the nomenclature defined in the equations (Section 3.1). Table 3 defines the relevant parameters, which are discussed further below.

`COMDAT.002` (Appendix A) is used as input for the first run, where parameters 4, 5, 6 (p_b, q_b, r_b in rad/s) and 28 and 29 (ϕ_o *and* θ_o in rad) are estimated. Parameters 31, 32, 33 (the position x, y, z in ft of the accelerometers in ship body axes) are set to constant values. A mechanism to ensure that the motion parameters are not optimised using the equations for *X*, *Y*, and *Z* (subroutine `Derivs`, Appendix B) was to use weighting parameters 42, 43, and 44 which are set to zero. The state weighting matrix (D1) is also set with large numbers for the Euler angles and small ones for the other states. This has the effect of conditioning the parameters so that they will be weighted towards optimisation by only using the angular state equations. An example of running *Compat* is shown below.

```
<blackjack /arneya/compat> Compat
 COMDAT.xxx File Number?
2
 COMDAT.002 opened.

 Input File?
20091158_Out
 20091158_Out    opened.

 ***** NNo > Data file size  - Data array reduced from 2500 to 1790
 points
  ITERATION NUMBER          0
  ITERATION NUMBER          1
```

```
  ITERATION NUMBER          2
  ITERATION NUMBER          3
            .
            .
  ITERATION NUMBER         23
  ITERATION NUMBER         24
STOP
<blackjack /arneya/compat>
```

Table 3. Equation Nomenclature and Equivalent Computer Symbols

Parameter Number	Equation Nomenclature	Computer Symbol	Comments
1	a_{x_b}	BAX	Accelerometer offsets
2	a_{y_b}	BAY	
3	a_{z_b}	BAZ	
4	p_b	BP	Angular rate offsets
5	q_b	BQ	
6	r_b	BR	
25	U_o	U0	Initial velocities
26	V_o	V0	
27	W_o	W0	
28	ϕ_o	PHI0	Initial attitudes
29	θ_o	TH0	
31	x	BXCG	Accelerometer position in ship body axes
32	y	BYCG	
33	z	BZCG	
38	Z_o	Z0	Initial vertical displacement
42	-	WX	Weighting parameters
43	-	WY	
44	-	WZ	

Note that the number of data lines read in is set to 2500 ($2500 * 0.05 = 125\ s$ data run) in `COMDAT.002`, but *Compat* will automatically adjust for data files smaller than this. File `COMOUT.FFG` contains run-time information, most details of which will not be discussed

here. The part of COMOUT.FFG of particular interest at this stage is towards the end of the file where the estimated parameters are given along with the Cramer-Rao (C-R) bound. The relevant part of the file is duplicated below.

PARAMETER	STATUS	A.P.	WEIGHT	ANSWER	C-R BOUND
4	1	.000000	99999.000	-.020238	.000012
5	1	.000000	99999.000	.000979	.000007
6	1	.000000	99999.000	.000044	.000001
28	1	.000000	99999.000	-.006754	.000638
29	1	.000000	99999.000	-.008442	.000358

As a general rule, if the C-R bound is less than one tenth of the estimated parameter (ANSWER), then a high level of confidence can be attached to the estimate. As can be seen above, a very high degree of confidence is associated with the estimates of the angular rate offsets, p_b, q_b, and r_b, (4, 5, and 6), although the confidence level for the initial attitudes, ϕ_o and θ_o, is lower. This is because the attitude initial conditions are obtained from mean data rather than measured data. Figure 9 shows a comparison of the measured rates with the calculated rates determined by *Compat,* and Figure 10 shows a comparison of the measured attitudes (derived from accelerometers for roll and pitch, compass for yaw) with the calculated attitudes.

COMDAT.004 (Appendix A) is used for the second run where parameters 1, 2, and 3 (offsets in accelerometer measurements in ft/s^2), 25, 26, and 27 (initial U, V, and W in ft/s), and 38 (initial Z in ft) are estimated. Parameters 31, 32, and 33 remain constant (as for COMDAT.002), but parameters 42, 43, and 44 are set to unity so that the derivative equations for X, Y, and Z are used (subroutine DERIVS, Appendix B). Parameters 4, 5, 6, 28, and 29 are set constant to the values determined in the previous run using COMDAT.002 as input. The state weighting matrix (D1) should also be set with small numbers for the Euler angles and large numbers for the other states. An example of running *Compat* is shown below.

```
<blackjack /arneya/compat> Compat
 COMDAT.xxx File Number?
4
 COMDAT.004 opened.

 Input File?
20091158_Out
 20091158_Out    opened.

  ***** NNo > Data file size  - Data array reduced from 2500 to 1790
  points
   ITERATION NUMBER           0
   ITERATION NUMBER           1
              .
              .
   ITERATION NUMBER          23
   ITERATION NUMBER          24
STOP
<blackjack /arneya/compat>
```

Again, examining file COMOUT.FFG gives the parameters and the Cramer-Rao bounds.

PARAMETER	STATUS	A.P.	WEIGHT	ANSWER	C-R BOUND
1	1	.109218	99999.000	-.055403	.000386
2	1	1.247285	99999.000	.777414	.000677
3	1	-.120199	99999.000	-.316788	.000107
25	1	7.829200	99999.000	19.176580	.020535
26	1	.000000	99999.000	.626917	.035006
27	1	.000000	99999.000	-1.252886	.004925
38	1	-2.317998	99999.000	1.839305	.096327

It can be seen from the Cramer-Rao bounds that all the estimated parameters have a high confidence level. The final product (i.e. the ship motion) is given in file `var.dat`, which is now transferred back to a Macintosh using ftp in the text mode via program *Versaterm Pro*, so that the motion effects may be removed from the measured data.

It should be noted at this stage that when running *Compat* for a number of different data files (xxxxxxxx_Out files), any COMDAT.002 file set up for ship motion may be used, but the COMDAT.004 file must be edited with the specific parameters 4, 5, 6, 28, and 29 found in a previous run using COMDAT.002.

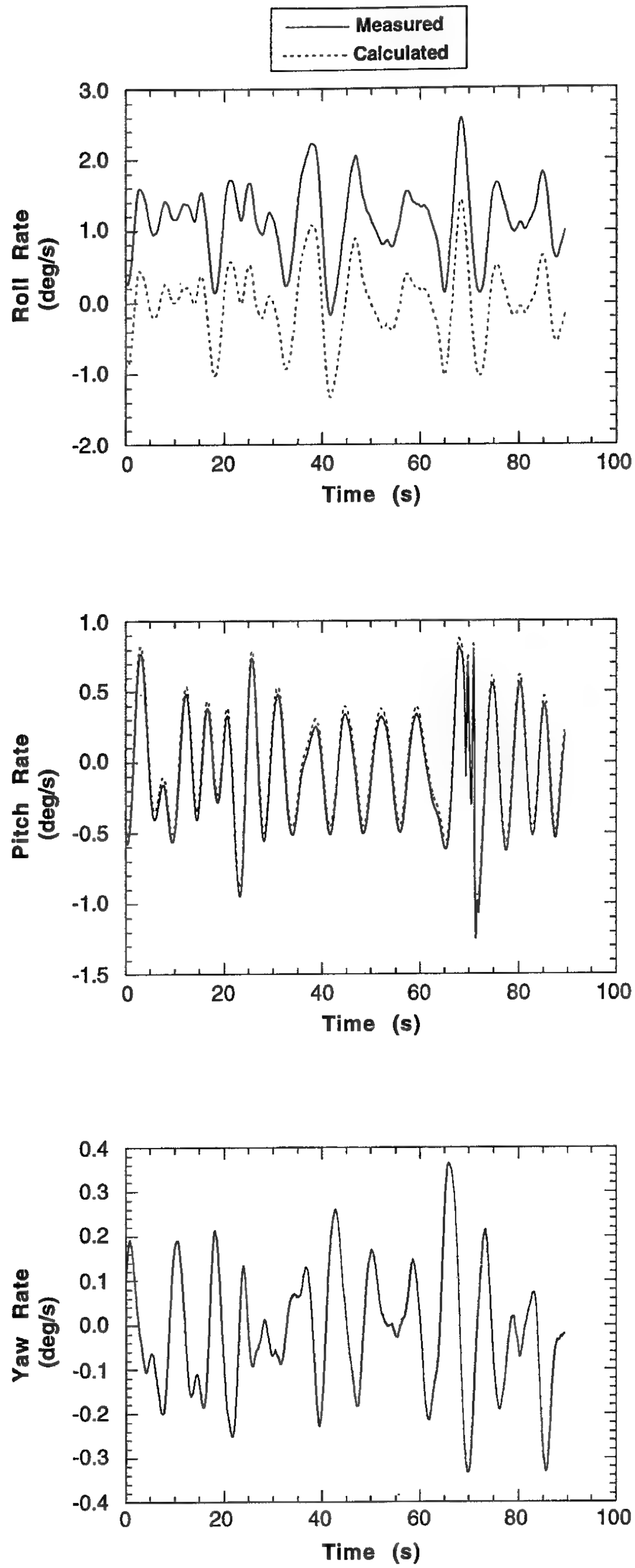


Figure 9. Measured Angular Rates Compared With Calculated Angular Rates

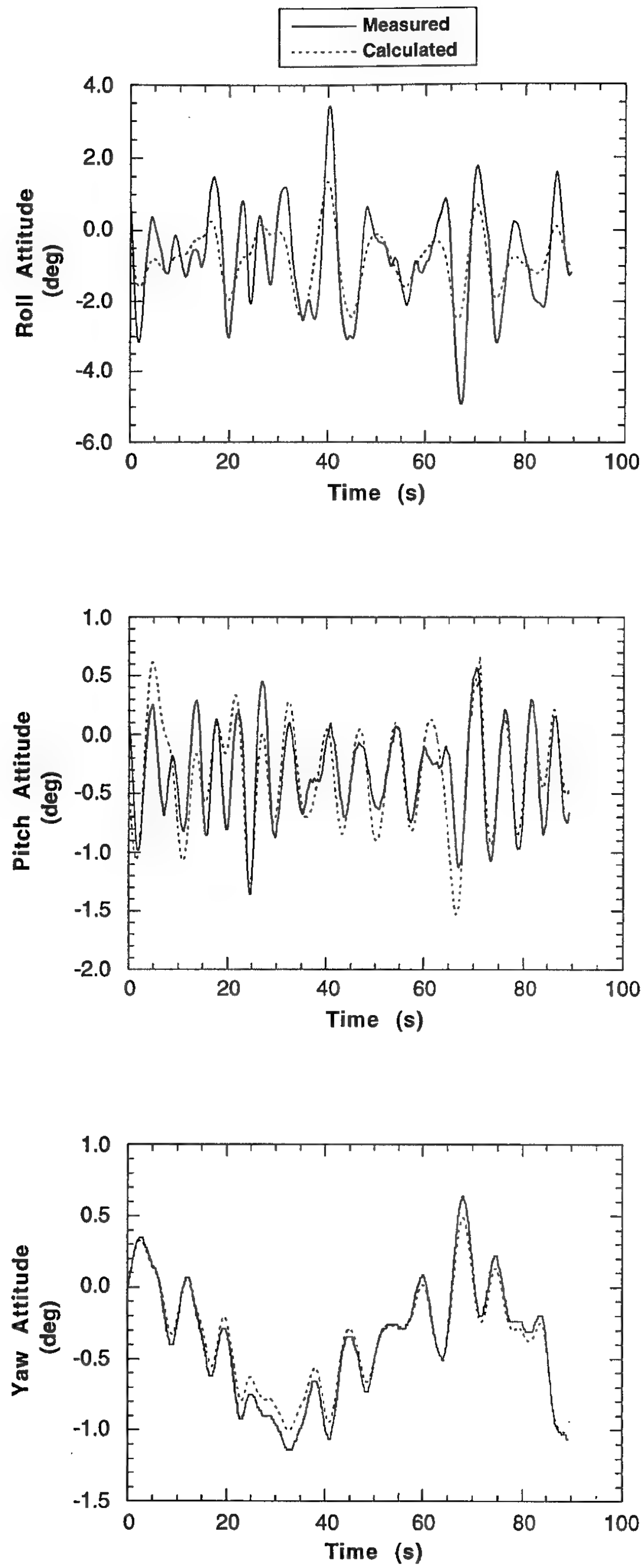


Figure 10. Measured Attitudes Compared With Calculated Attitudes

4. REMOVING SHIP MOTION FROM AIRWAKE DATA

Ship motion effects are removed from the measured anemometer data using a program on the Macintosh (written in Fortran) called *AWSM* (Airwake Without Ship Motion). This section describes how *AWSM* removes these effects and gives examples of running *AWSM* and associated utility programs.

4.1 Program *AWSM*

AWSM reads in calculated ship motion (from *Compat*, see Section 3) and measured airwake data (from *MacShipRefine*, see Ref. 9), removes the motion effects, then outputs the corrected airwake data to file `xxxxxxxx Output`. The position of each of the anemometers relative to the centre of ship motion is first determined, depending on the position of the mobile anemometer mast (Fig. 2). Table 4 gives the displacement of the base of the mobile mast for each of the mast positions, as well as the position of the cup and aerovane anemometers.

Table 4. Mobile Mast Base, Cup, and Aerovane Anemometer Positions

Anemometer	x_{base} (ft)	y_{base} (ft)	z_{base} (ft)
Position 1	-118.7	-17.1	-15.3
Position 2	-118.7	-10.5	-15.3
Position 3	-118.7	0.0	-15.3
Position 4	-118.7	10.5	-15.3
Position 5	-118.7	17.1	-15.3
Position 6	-142.5	-17.1	-15.8
Position 7	-142.5	-10.5	-15.8
Position 8	-142.5	0.0	-15.8
Position 9	-142.5	10.5	-15.8
Position 10	-142.5	17.1	-15.8
Position 11	-163.5	-10.5	-16.2
Position 12	-163.5	0.0	-16.2
Position 13	-163.5	10.5	-16.2
Aerovane	-181.9	2.1	-29.93
Stbd Cup	-181.9	21.7	-21.7
Port Cup	-181.9	-21.7	-21.7

The anemometers on the mast are offset from the base along the X and Z axes as shown in Table 5. The position of each of the anemometers in the array relative to the ship centre of motion is calculated as follows:

Table 5. Offsets in Anemometers Relative to Mast Base

	Top	Mid	Low
x_{lat} (ft)	0.0	1.48	1.48
x_{vert} (ft)	0.0	1.48	1.48
z_{long} (ft)	-31.5	-21.0	-10.5
z_{lat} (ft)	-31.83	-21.33	-10.83

For each anemometer array (top, mid, and low),

$$\Delta x_{lat} = x_{base} + x_{lat}$$
$$\Delta x_{vert} = x_{base} + x_{vert}$$
$$\Delta y_{long} = y_{base}$$
$$\Delta y_{vert} = y_{base}$$
$$\Delta z_{long} = z_{base} + z_{long}$$
$$\Delta z_{lat} = z_{base} + z_{lat}$$

The corrected anemometer velocities in ship body axes for each array are given by

$$u_c = u_m - \Delta U_{ship} + q\Delta z_{long} - r\Delta y_{long}$$
$$v_c = v_m - \Delta V_{ship} + r\Delta x_{lat} - p\Delta z_{lat}$$
$$w_c = w_m - \Delta W_{ship} + p\Delta y_{vert} - q\Delta x_{vert}$$

where

$$\Delta U_{ship} = U - U_{mean}$$
$$\Delta V_{ship} = V - V_{mean}$$
$$\Delta W_{ship} = W - W_{mean}$$

Note that the incremental ship velocities (fluctuations about the mean velocity), rather than the actual ship velocities, are subtracted from the measured airwake velocities. This is to allow for the case where all the measured airwake velocity is due to the ship velocity. For example, in still air with an actual ship velocity of 10 ft/s, the measured airwake will be 10 ft/s. Thus, if the actual ship velocity was subtracted, the corrected airwake velocity would be zero which is clearly incorrect. It should also be noted that one of the key assumptions in determining the ship motion using *Compat* is that the mean lateral and vertical ship velocities in body axes are zero.

AWSM also transforms the velocities from ship body axes to ship-carried vertical axes, which is the desired format for comparison purposes with wind tunnel measurements and for use as an airwake data base in the computer simulation. The ship-carried vertical axes origin is coincident with the ship body axes (Fig. 11), but the Z axis is aligned vertically downwards, i.e. along the local *g* vector.

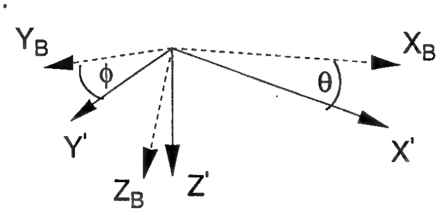


Figure 11. Ship-carried Vertical Axes (X'Y'Z', Z' Parallel to Z_E)

The matrix used to transform from ship body axes to ship-carried vertical axes is shown below.

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta\sin\phi & \sin\theta\cos\phi \\ 0 & \cos\phi & -\sin\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix} \begin{bmatrix} u_c \\ v_c \\ w_c \end{bmatrix}$$

4.2 Preparing Input Data

The measured airwake data file which is used as input to *AWSM* must be in the format defined below:

Column 1:	Time
Columns 2-4:	u_m, v_m, w_m for the top anemometer array
Columns 5-7:	u_m, v_m, w_m for the mid anemometer array
Columns 8-10:	u_m, v_m, w_m for the low anemometer array
Columns 11-12:	V_{ship}, Ψ_{ship}
Columns 13-14	V_{ref}, Ψ_{ref}
Columns 15-16:	V_{stbd}, Ψ_{stbd}
Columns 17-18:	V_{port}, Ψ_{port}

In order to create this input file, a number of utility programs (written in Fortran) are available for use on Macintosh computers.

Program *MacTrans* is first used to obtain data in imperial units from the data file generated using program *MacShipRefine*. Appendix C contains a copy of file `AIRWAKE.BLK`, which gives the channels required in the correct order for use with utility program *Convert* outlined below. Before running *MacTrans*, file `AIRWAKE.BLK` should be renamed to `TRANS.BLK`. *MacTrans* is then run as shown below:

```
[TRANS version date 12-FEB-91]

GO STRAIGHT TO EVENT LOOP?
I/P FILENAME = 20091158
Wind 60 deg, 20 kn - Position 10
File 20091158 (filtered)

I/P FILE RECORDED ON 17-FEB-93   AT 10:11:28

INTEGN INT = 0.0000E+00; RUN CPU TIME =    3 MIN. 24.47 SEC.

TIME FROM 0.0000E+00 TO 8.9500E+01 IN STEPS OF 5.0000E-02

*PRC
PRINTING IN COLUMNS :

BLKS
L1,L2,L3
<CR>
IS O/P TO TTY REQRD : N
[ PRC  Output, for this run, going to DSK:20091158.CO0    ]
*GOE
** RUNNING **
*EXI
```

The resulting data file, `20091158.COO`,[1] is then used as input to program *AWSM.*

The utility program *Convert* may be used to change the *MacTrans* column format into multiple sequential columns, which is also more easily read in by other programs. Running program *Convert* results in file `20091158.COO Out`. The operation of this program is similar to *FFGConvert(Attitudes)* [2] (see Section 3.2).

4.3 Running *AWSM*

When program *Compat* creates an output file containing calculated motion data, the file is always named `var.dat`. When multiple runs with different data files are used, it is suggested that each file be renamed depending on the run.[3] For the example used throughout this report, the `var.dat` file is renamed `20091158var.dat`.

Program *AWSM* begins by flashing an FFG-7 picture to the screen. The user clicks once on this picture to bring a window to the screen prompting for the name of the *Compat* output file (Fig. 12).

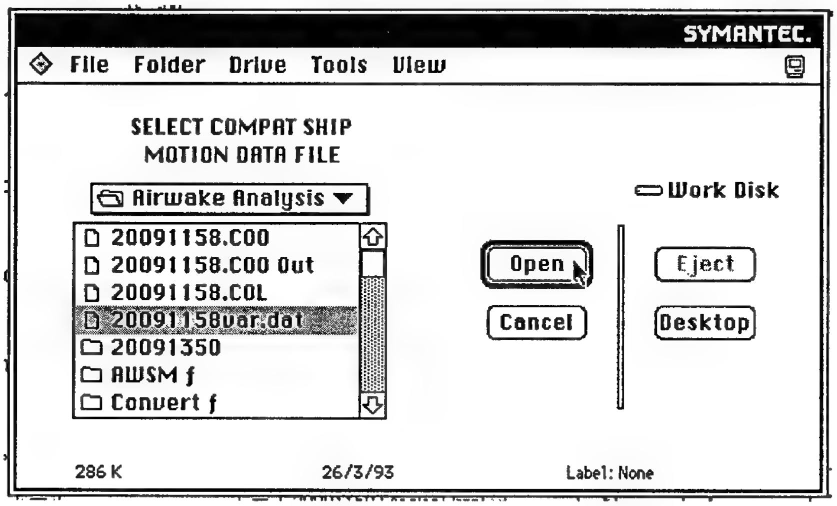


Figure 12. Window Prompt for Ship Motion Data File

After choosing the desired motion data file, the user is then prompted for the measured anemometer data file (Fig. 13).

---

1 Program *MacTrans* has an automatic file naming feature. If a `xxxxxxxx.COL` file already exists in the same folder, the new file will be named `xxxxxxxx.COO` and so on up to `xxxxxxxx.C99`.

2 Programs *Convert*, *FFGConvert(Attitudes)*, and *FFGConvert(Heave)* are basically the same program with minor changes included in data manipulation.

3 If a large number of runs are to be made, the source code for *Compat*, namely `compat.f`, should be edited to automatically name the `var.dat` file.

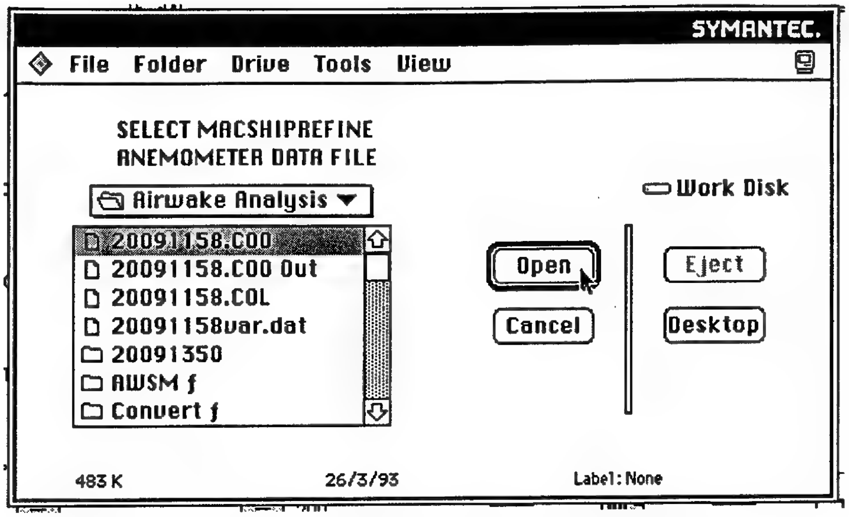


Figure 13. Window Prompt for Anemometer Data File

The user is then prompted for the position of the mobile anemometer file for that particular run (in this case position 10), as shown in Fig. 14.

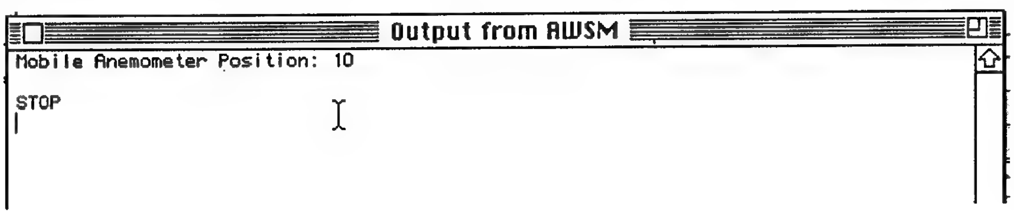


Figure 14. Window Prompt for Anemometer Position

The resulting data file, in this case `20091158 Output`, contains airwake data corrected for motion effects and may be compared directly with the uncorrected data in file `20091158.C00 Out` (Section 4.2). An example of such a comparison is given in Section 5.3.

5. RESULTS

5.1 Motion Analysis Sensitivity to Data Time Length

It is generally accepted that analysis of ship motion requires data measured over a long time period. During the airwake trial, it was impractical to record data at each of the anemometer positions for much more than 90 seconds.[1] To check the validity of the assumptions used in the motion analysis over relatively short time periods, it was decided to examine the results using the same data file for varying time lengths. The file 20091347 was chosen, as the data were recorded for 118 s (considerably longer than the usual 90 s) and the magnitude of the ship motion for this case was relatively large (see Appendix D).

Figures 15 and 16 show comparisons of the calculated attitudes and velocities respectively for data time lengths of 60, 75, 90, 105, and 118 seconds.

---

1 In order to obtain some of the required high wind-over-deck velocities it was necessary for the ship to steam at full speed. Due to the increase in fuel consumption at this speed, the data were recorded at each of the anemometer positions for a maximum of 60 seconds rather than the usual 90 seconds.

As can be seen from Fig. 15, the calculated attitudes give similar results throughout the time periods examined, indicating that the method for determining the attitudes is relatively insensitive for data recorded for 60 s or more. Examination of Fig. 16 shows that the vertical velocity component gives similar results for the different time periods, but the longitudinal component gives slight differences and the lateral component varies for each data length. These differences suggest that some of the assumptions used for determining the velocities may not be good. Some indication of the confidence level of the estimates is given by the Cramer-Rao bounds for each of the parameters. Table 6 gives the Cramer-Rao bounds for the parameters estimated for each of the different data time periods and Fig. 17 shows a comparison of the Cramer-Rao bounds for the accelerometer offsets.

Table 6. Cramer-Rao Bounds for Various Data Time Periods

Parameter		Cramer-Rao Bounds				
Name	No.	60 s	75 s	90 s	105 s	118 s
p_b	4	0.000031	0.000034	0.000025	0.000020	0.000016
q_b	5	0.000010	0.000007	0.000005	0.000004	0.000003
r_b	6	0.000001	0.000001	0.000001	0.000000	0.000000
ϕ_o	28	0.001069	0.001467	0.001302	0.001225	0.001092
θ_o	29	0.000349	0.000311	0.000268	0.000241	0.000223
a_{x_b}	1	0.000638	0.000391	0.000364	0.000225	0.000244
a_{y_b}	2	0.001325	0.001244	0.001361	0.001424	0.000863
a_{z_b}	3	0.000340	0.000218	0.000133	0.000086	0.000063
U_o	25	0.021544	0.018110	0.016181	0.013652	0.013135
V_o	26	0.045881	0.053726	0.070686	0.086244	0.058998
W_o	27	0.010628	0.008361	0.006167	0.004743	0.003850
Z_o	38	0.139626	0.136450	0.120662	0.106561	0.098713

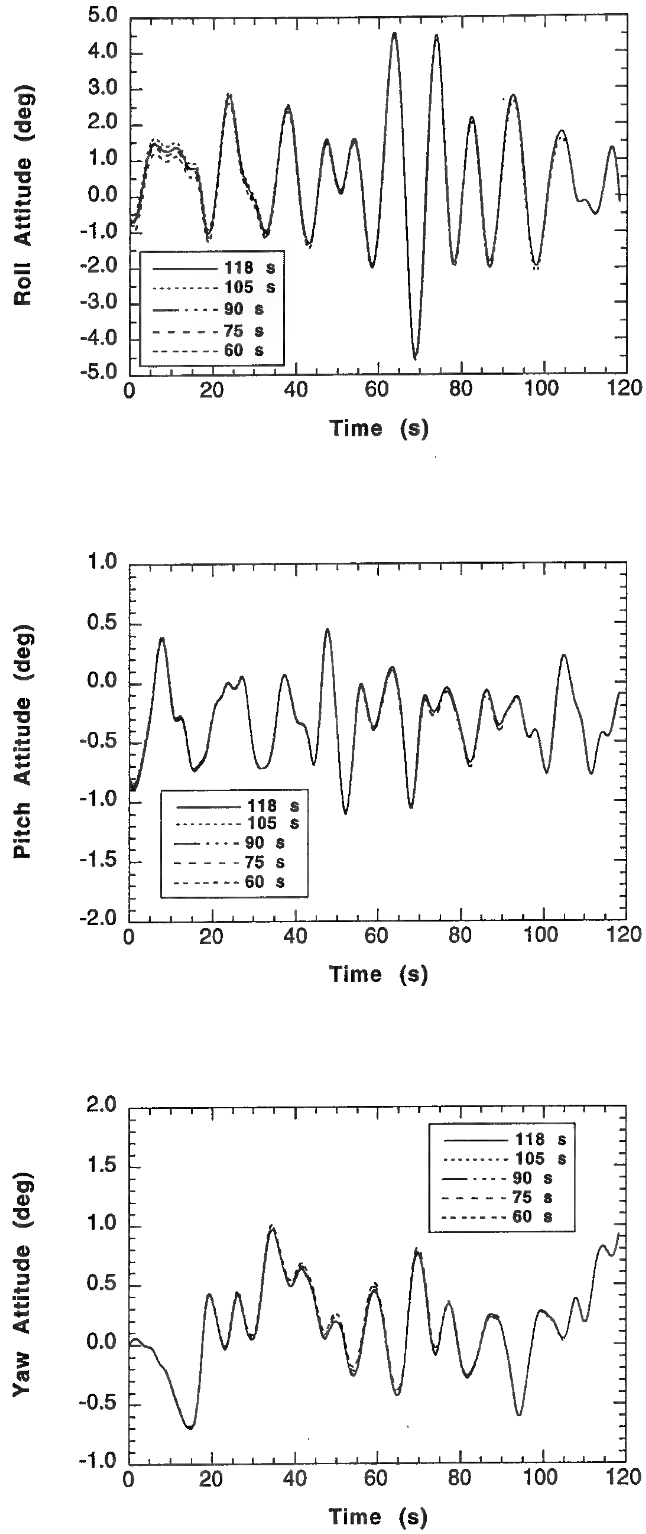


Figure 15. Comparison of Calculated Ship Attitudes for Data of Various Time Periods

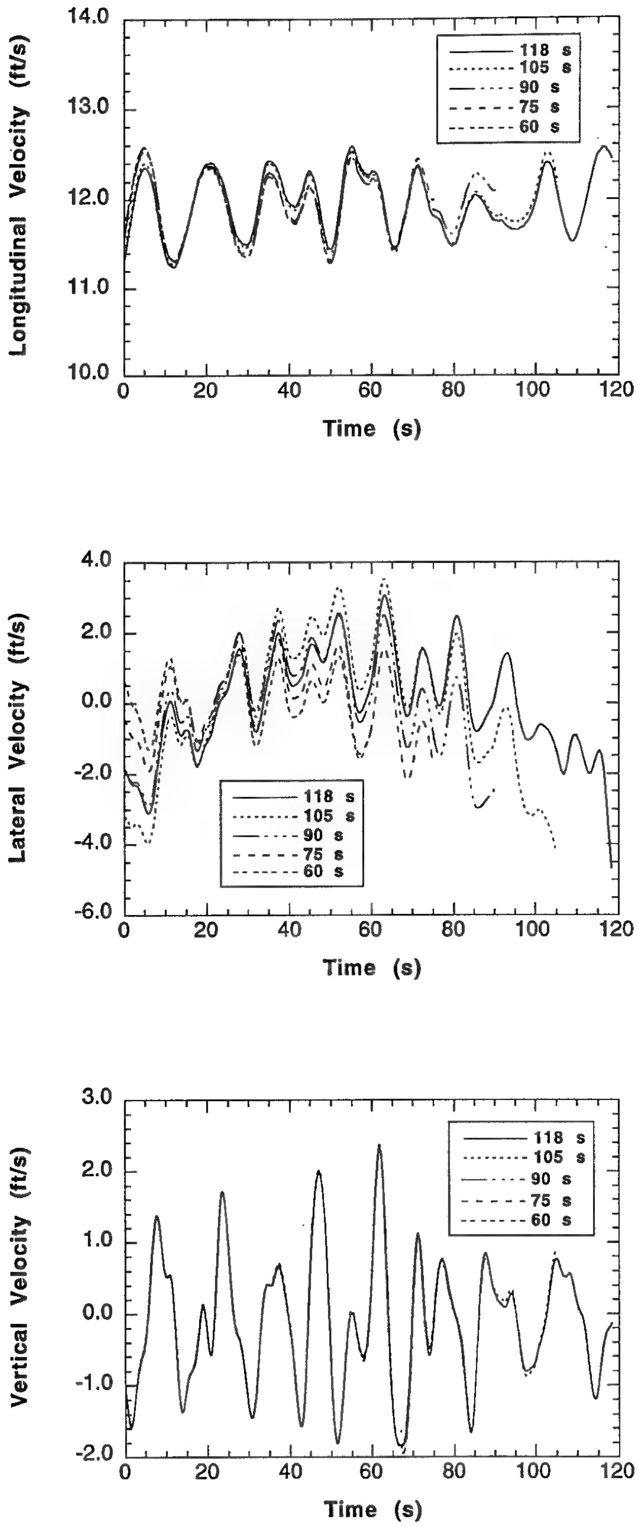


Figure 16. Comparison of Calculated Ship Velocities for Data of Various Time Periods

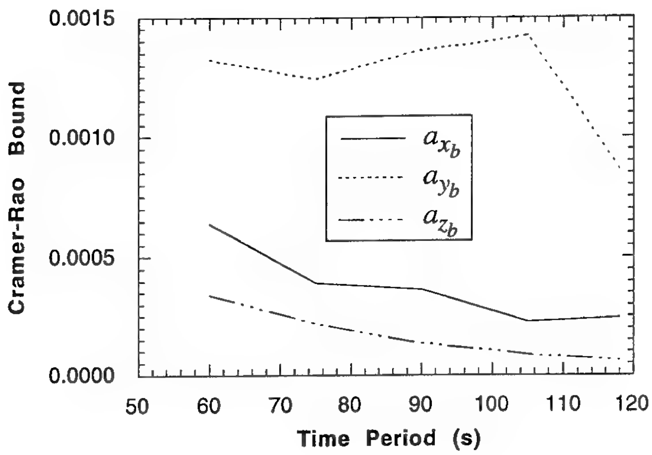


Figure 17. Comparison of Cramer-Rao Bounds for Accelerometer Offsets

It can be seen from Fig. 17 that the C-R bounds for the estimates of the longitudinal and vertical accelerometer offsets, a_{x_b} and a_{z_b} (which, in effect, determine the calculated velocities), steadily decrease with an increase in the length of recorded data. This suggests that the basic assumptions are correct and the longer the length of data recorded, the higher the confidence level for the estimated offsets. However, the C-R bound for the lateral accelerometer offset, a_{y_b}, is much larger than that for the other two offsets and does not show a consistently decreasing trend with time. This suggests that the assumption that the average lateral velocity is zero may be in error, perhaps due to ocean currents. To improve the accuracy of this technique in determining the lateral velocity component, the actual lateral velocity or displacement could be measured, e.g. by using a satellite navigation system.

5.2 Determining Worst Case Ship Motion

Before proceeding with determining ship motion and removing these effects from all the data files (a total of 146 data runs), it was decided to use *Compat* to find the approximate magnitude of the motion for each of the wind-over-deck conditions. Once the worst case (i.e. largest linear velocities and angular rates) was found, the airwake without ship motion would be determined for that complete case. Table 7 gives a list of the files which were initially processed.

The order in which the files in Table 7 were processed was largely historical, as discussed next. By examining the raw data, a number of possibilities presented themselves as the worst case. The initial examinations were done for the mobile mast positioned over the bullseye (position 8). At this stage, the 180° 10 kn wind-over-deck cases appeared to be giving the greatest magnitudes of ship motion, so these files were concentrated upon to finalise the technique used to determine ship motion. Once the technique was finalised, a representative file from each of the wind-over-deck conditions which had not yet been examined was processed for a deck position resulting in the greatest effect on the anemometers (position 10 or, if that was not available, position 5). It should be noted that for the 90° 20 kn case (where HF radio corrupted many of the digital channels), it was found that the files for positions 5 [1]

[1] Position 10 was not measured.

and 1 (21091403 and 21091409 respectively) also had errors in the yaw rate measurements,[1] which resulted in incorrect ship motion results.

Table 7. Initial Selected Wind-Over-Deck Conditions

Wind-Over-Deck Condition	File Name	Mobile Mast Position
Ship Stationary	16091506	8
00° 10 kn	19091053	10
00° 20 kn	19091624	8
00° 35 kn	19091714	5
30° 10 kn	20091424	8
30° 20 kn	18091428	10
30° 35 kn	21091243	8
60° 10 kn	18091529	10
60° 20 kn	20091158	10
90° 10 kn	18091626	8
90° 20 kn	21091424	11
135° 10 kn	20091350	5
135° 10 kn	20091315	10
180° 10 kn	20090930	6
180° 10 kn	20090956	8
180° 10 kn	20091000	9
180° 10 kn	20090920	13

An *Excel* (©Microsoft) document (`Stats Template`) was set up to find the maximum, minimum, mean, and standard deviation of the ship motion variables. The output files from *Compat* are pasted directly into the first 14 columns of the *Excel* document with the statistics being given in the next 14 columns. After examination of all the files, it was determined that the worst ship motion occurred for the 180° 10 kn and the 135° 10 kn cases. At this stage it was decided to concentrate on the 135° 10 kn case, as this seemed to have more reasonable motion data than the 180° 10 kn case.[2] The files for the 135° 10 kn case are shown in Table 8.

Statistics for the 135 deg 10 kn case are presented in Appendix D with statistics for the remaining files in Table 7 given in Appendix E.

5.3 Comparing Measured with Corrected Airwake Data

Having determined the ship motion for the entire 135° 10 kn case, program *AWSM* was used to determine the airwake. Table 9 gives the statistics of the top anemometer array for position 5, comparing measured data with data corrected for motion effects, while Figure 18 shows the time histories of the lateral and vertical components. The corrections for the longitudinal velocity component for this case were so small as to be negligible.

---

1 The errors in the yaw rate measurements consisted of a large step part way through the time history, which could possibly be corrected after further analysis.

2 The vertical displacements, *Z*, for the 180° 10 kn case appear to be abnormally large when compared to all the other cases. This may however be true because the ship was almost stationary to achieve 10 kn wind-over-deck from behind, and thus the ship was not cutting through the waves but rather wallowing on them.

Examination of Fig. 18 shows that, at a given point in the time history, the magnitude of the airwake velocity when corrected for ship motion differs markedly from that when uncorrected, although the mean velocity is almost identical.

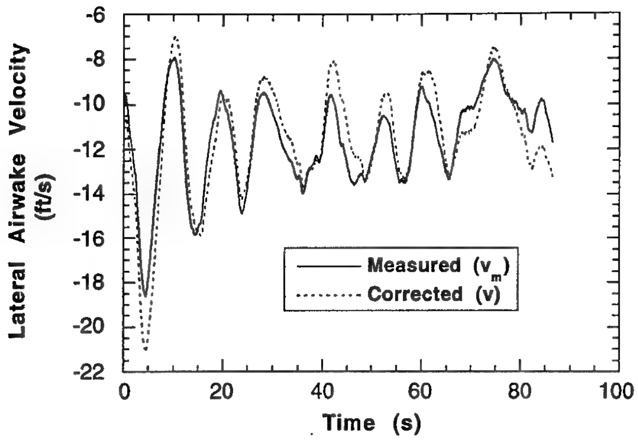
Table 8. Files for 135° 10 kn Case

Filename	Mast Position
20091337	1
20091340	2
20091343	3
20091347	4
20091350	5
20091330	6
20091334	7
20091307	8
20091311	9
20091315	10
20091326	11
20091323	12
20091319	13

Table 9. Statistics for Top Anemometer Array at Position 5 for 135° 10 kn Case

Statistics	u_m (ft/s)	u (ft/s)	v_m (ft/s)	v (ft/s)	w_m (ft/s)	w (ft/s)
Minimum	5.37	5.77	-18.62	-21.10	-6.78	-8.06
Maximum	12.91	13.87	-7.91	-6.97	0.00	1.51
Mean	10.65	10.67	-11.56	-11.52	-3.75	-3.85
Std Deviation	1.28	1.54	2.07	2.52	0.97	1.59

The maximum corrections to the lateral velocity component are approximately 3.3 ft/s for ship linear velocity (ΔV_{ship}) and 2.0 ft/s ($p\Delta z_{lat}$) due to rolling. The time at which the correction for ship linear velocity is maximum is generally when the correction due to rolling is minimum, and vice versa. Even though these corrections have been applied, Fig. 18 indicates a signal having approximately the same period as the ship motion. Preliminary study of a number of cases suggests that this is due to large eddy turbulence in the earth's boundary layer, rather than vortices being shed from the sharp edges of the ship.



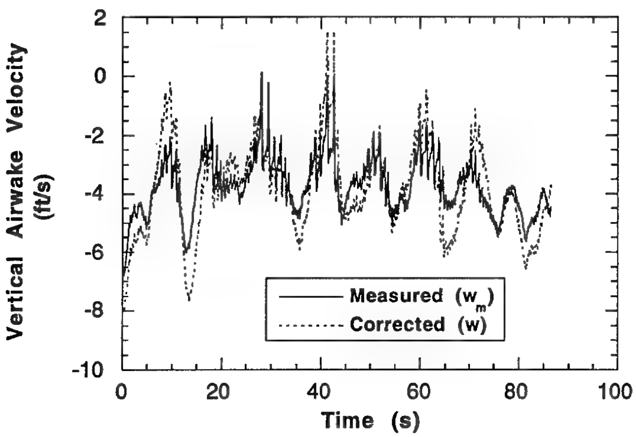


Figure 18. Comparison of Measured Data with Data Corrected for Motion Effects

6. CONCLUDING REMARKS

A procedure has been presented here for determining ship motion from limited measured data and removing this effect from measured airwake data. The same technique for determining ship motion may be used in future trials, with a notable difference being that if attitude is measured directly, then it is not necessary to use the mean values derived from accelerometers. The accuracy of the calculated ship velocity may be improved by lengthening the data recording time and by including extra velocity and displacement information from a satellite navigation system.

It has been shown that the mean of the measured airwake is approximately the same as the mean of the airwake corrected for motion effects. With hindsight, this is an inevitable result, as the mean angular rates must approach zero and the ship is assumed to have mean linear velocities approaching zero in the motion analysis. For the applications of using the measured data as a mean flow data base for the helicopter/ship model, or for comparison with wind tunnel results, the procedure for removing motion effects from the airwake is therefore not warranted. However, it should be noted that the technique for determining ship motion developed here has also been applied to determining the motion of a 'Perth' class DDG destroyer and for calculating the position of the flight deck of HMAS Jervis Bay during a Black Hawk First of Class Flight Trial.

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APPENDIX A - INPUT FILES COMDAT.002 AND COMDAT.004

Parameter	Definition	Parameter	Definition
NPM	No. of parameters	ITR	No. of iterations
MU	No. of control inputs (=9; $a_x, a_y, a_z, p, q, r, \dot{p}, \dot{q}, \dot{r}$)	ITO	No. of iterations with a priori values applied
NS	No. of states (=9; $U, V, W, \phi, \theta, \psi, X, Y, Z$)	NAVG	No. of points used for least squares fit of initial data point
MZ	No. of measurements (=9; $U_m, V_m, W_m, \phi_m, \theta_m, \psi_m, X_m, Y_m, Z_m$)	DTT	Data time interval
ISK	No. of lines skipped in data file	FINK	Program variable
NN	No. of lines in data file		

COMDAT.002

```
  NPM   MU   NS   MZ  ISK    NN  ITR  ITO  NAVG
   44    9    9    9    2  2500   25    2    10
  DTT   FINK
 0.05  0.001
STATES REFS STATUS
U       1     1
V       2     1
W       3     1
PHI     4     1
THETA   5     1
PSI     6     1
X       7     1
Y       8     1
Z       9     1
MEAS   REFM STATUS   I.C.    D1
U       1     1       0  0.000001
V       2     1       0  0.000001
W       3     1       0  0.000001
PHI     4     1       0  100000.0
THETA   5     1       0  100000.0
PSI     6     1       0  100000.0
X       7     1       0  0.000001
Y       8     1       0  0.000001
Z       9     1       0  0.000001
PARAMS REFP STATUS  A PRIORI  WEIGHT
BAX     1     0       0.00   99999.0
BAY     2     0       0.00   99999.0
BAZ     3     0       0.00   99999.0
BP      4     1  -0.000000   99999.0
BQ      5     1  -0.000000   99999.0
BR      6     1   0.000000   99999.0
LAX     7     0       0.00   99999.0
LAY     8     0       0.00   99999.0
LAZ     9     0       0.00   99999.0
LP     10     0       0.00   99999.0
LQ     11     0       0.00   99999.0
LR     12     0       0.00   99999.0
BU     13     0       0.00   99999.0
BV     14     0       0.00   99999.0
BW     15     0       0.00   99999.0
BPHI   16     0       0.00   99999.0
BTHETA 17     0       0.00   99999.0
BPSI   18     0       0.00   99999.0
LU     19     0       0.00   99999.0
LV     20     0       0.00   99999.0
LW     21     0       0.00   99999.0
LPHI   22     0       0.00   99999.0
LTHETA 23     0       0.00   99999.0
LPSI   24     0   0.000000   99999.0
```

U0	25	0	0.000000	99999.0
V0	26	0	0.00	99999.0
W0	27	0	0.00	99999.0
PHI0	28	1	-0.000000	99999.0
TH0	29	1	-0.000000	99999.0
PSI0	30	0	0.00	99999.0
BXCG	31	0	-87.7	99999.0
BYCG	32	0	4.33	99999.0
BZCG	33	0	-14.9	99999.0
BDTHT	34	0	0.00	99999.0
BDPHI	35	0	0.00	99999.0
X0	36	0	0.00	99999.0
Y0	37	0	0.00	99999.0
Z0	38	0	0.00	99999.0
BX	39	0	0.00	99999.0
BY	40	0	0.00	99999.0
BZ	41	0	0.00	99999.0
WX	42	0	0.00	99999.0
WY	43	0	0.00	99999.0
WZ	44	0	0.00	99999.0

COMDAT.004

NPM	MU	NS	MZ	ISK	NN	ITR	ITO	NAVG
44	9	9	9	2	2500	25	2	10

DIT	FINK
0.05	0.001

STATES	REFS	STATUS
U	1	1
V	2	1
W	3	1
PHI	4	1
THETA	5	1
PSI	6	1
X	7	1
Y	8	1
Z	9	1

MEAS	REFM	STATUS	I.C.	D1
U	1	1	0	100000.0
V	2	1	0	100000.0
W	3	1	0	100000.0
PHI	4	1	0	0.000001
THETA	5	1	0	0.000001
PSI	6	1	0	0.000001
X	7	1	0	100000.0
Y	8	1	0	100000.0
Z	9	1	0	100000.0

PARAMS	REFP	STATUS	A PRIORI	WEIGHT
BAX	1	1	0.109218	99999.0
BAY	2	1	1.247285	99999.0
BAZ	3	1	-0.120199	99999.0
BP	4	0	-0.020238	99999.0
BQ	5	0	0.000979	99999.0
BR	6	0	0.000044	99999.0
LAX	7	0	0.00	99999.0
LAY	8	0	0.00	99999.0
LAZ	9	0	0.00	99999.0
LP	10	0	0.00	99999.0
LQ	11	0	0.00	99999.0
LR	12	0	0.000000	99999.0
BU	13	0	0.00	99999.0
BV	14	0	0.00	99999.0
BW	15	0	0.00	99999.0
BPHI	16	0	0.00	99999.0
BTHETA	17	0	0.00	99999.0
BPSI	18	0	0.00	99999.0
LU	19	0	0.00	99999.0
LV	20	0	0.00	99999.0
LW	21	0	0.00	99999.0
LPHI	22	0	0.00	99999.0
LTHETA	23	0	0.00	99999.0
LPSI	24	0	0.00	99999.0
U0	25	1	7.8292	99999.0
V0	26	1	0.00	99999.0
W0	27	1	0.00	99999.0
PHI0	28	0	-0.006754	99999.0

TH0	29	0	-0.008442	99999.0
PSI0	30	0	0.00	99999.0
BXCG	31	0	-87.7	99999.0
BYCG	32	0	4.33	99999.0
BZCG	33	0	-14.9	99999.0
BDTHT	34	0	0.00	99999.0
BDPHI	35	0	0.00	99999.0
X0	36	0	0.00	99999.0
Y0	37	0	0.00	99999.0
Z0	38	1	-2.317998	99999.0
BX	39	0	0.00	99999.0
BY	40	0	0.00	99999.0
BZ	41	0	0.00	99999.0
WX	42	0	1.00	99999.0
WY	43	0	1.00	99999.0
WZ	44	0	1.00	99999.0

APPENDIX B - PROBLEM SPECIFIC SUBROUTINES AND PROGRAM LINK FILE

Link

```
xlf -g compat.f consub.f deriv.f init.f resp.f rk4new.f -o CompatH
```

Deriv.f

```
      SUBROUTINE DERIVS( F, NK, PARAM, UU, VAR, NSTS )
C
C     SUBROUTINE FOR INTEGRATING AIRCRAFT KINEMATIC EQUATIONS
C     FOR 6DOF COMPATIBILITY CHECKING
C
      REAL AX, AY, AZ, CVAR4, CVAR5, F( * ), P, PARAM( * )
      REAL Q, R, SVAR4, SVAR5, UU( * ), VAR( NSTS, * )
C
cAMA  GRAV=9.80665         ! m/s/s
      PARAMETER( GRAV=32.17405 ) ! ft/s/s
C
cAMA  Accelerations and rates are read in as control inputs from a data
cAMA  file created by 'MANIP.FFG' which manipulates data from a 'TRANS'
cAMA  column print
c
cAMA  Included angular accelerations derived from filtered rates
C
      P = ( 1.0 + PARAM( 10 ) )*UU( 4 ) + PARAM( 4 )
      Q = ( 1.0 + PARAM( 11 ) )*UU( 5 ) + PARAM( 5 )
      R = ( 1.0 + PARAM( 12 ) )*UU( 6 ) + PARAM( 6 )
      pdot = uu(7)
      qdot = uu(8)
      rdot = uu(9)
c
C
      SVAR4 = SIN( VAR( 4, NK ) )
      CVAR4 = COS( VAR( 4, NK ) )
      SVAR5 = SIN( VAR( 5, NK ) )
      CVAR5 = COS( VAR( 5, NK ) )
      svar6 = sin( var( 6, nk ) )
      cvar6 = cos( var( 6, nk ) )
c
      Ax = UU( 1 ) + ( Q*Q + R*R )*PARAM( 31 ) - (P*Q-rdot)*PARAM( 32 )
     $     - (P*R+qdot)*PARAM( 33 ) - GRAV*SVAR5
      Ay = UU( 2 ) - (P*Q+rdot)*PARAM( 31 ) + ( P*P + R*R )*PARAM( 32 )
     $     - (Q*R-pdot)*PARAM( 33 ) + GRAV*CVAR5*SVAR4
      Az = UU( 3 ) - (P*R-qdot)*PARAM( 31 ) - (Q*R+pdot)*PARAM( 32 )
     $     + ( P*P + Q*Q )*PARAM( 33 ) + GRAV*CVAR5*CVAR4
C
      AX = ( 1.0 + PARAM( 7 ) )*Ax + PARAM( 1 )
      AY = ( 1.0 + PARAM( 8 ) )*Ay + PARAM( 2 )
      AZ = ( 1.0 + PARAM( 9 ) )*Az + PARAM( 3 )
C
C     CALCULATE DERIVATIVES
C
cAMA  Derivative equations which are integrated to give observations
cAMA  Equations are UDot,VDot,WDot,PhiDot,ThetaDot,PsiDot,XDot,YDot,ZDot
C
c      vel = sqrt(var(1,nk)**2 + var(2,nk)**2
c     $     + var(3,nk)**2)
      F( 1 ) = AX - Q*VAR( 3, NK ) + R*VAR( 2, NK ) ! U DOT
      F( 2 ) = AY - R*VAR( 1, NK ) + P*VAR( 3, NK ) ! V DOT
      F( 3 ) = AZ - P*VAR( 2, NK ) + Q*VAR( 1, NK ) ! W DOT
      F( 6 ) = ( Q*SVAR4 + R*CVAR4 )/CVAR5 ! PSI DOT
      F( 4 ) = P + F( 6 )*SVAR5            ! PHI DOT
      F( 5 ) = Q*CVAR4 - R*SVAR4           ! THETA DOT
cAMA        f( 7 ) = vel*cvar5*cvar6*param(42)    ! X Dot
cAMA        f( 8 ) = vel*cvar5*svar6*param(43)    ! Y Dot
cAMA        f( 9 ) = -vel*svar5*param(44)         ! Z Dot
      f( 7 ) = (var(1,nk)*cvar5*cvar6
     $         + var(2,nk)*(svar4*svar5*cvar6-cvar4*svar6)
     $         + var(3,nk)*(cvar4*svar5*cvar6+svar4*svar6))*param(42)
      f( 8 ) = (var(1,nk)*cvar5*svar6
     $         + var(2,nk)*(svar4*svar5*svar6+cvar4*cvar6)
     $         + var(3,nk)*(cvar4*svar5*svar6-svar4*cvar6))*param(43)
```

```
      f( 9 ) = (-var(1,nk)*svar5 + var(2,nk)*cvar5*svar4
     $          + var(3,nk)*cvar5*cvar4)*param(44)          ! Z Dot
c
      RETURN
      END
```

Init.f

```
*-----------------------------------------------------------------------
*
        SUBROUTINE PARAM_INIT( PARAM, DTT, IC_M, NAVG, Z, Z0, MZ, MZTS )
*
*       Subroutine to set initial condition parameters.
*
*       Modified by: M.L. Turner, SOG, ARL
*       Date: 4/6/'91
*
*-----------------------------------------------------------------------
C
C SUBROUTINE TO SET INITIAL CONDITIONS FOR PARAMETERS
C
C FOLLOWING ALLOWS FOR EITHER IDENTIFICATION OF INITIAL
C CONDITIONS, OR FOR UPDATING BASED ON IDENTIFIED BIAS
C AND SCALE FACTOR PARAMETERS - ASSUMING STATES ARE
C U(0), V(0), W(0), PHI(0), THETA(0), PSI(0)
C
        INTEGER IC_M( * ), NAVG, MZ, MZTS
C
        REAL AVG, DEN, DTT, NUM, PARAM( * ), SUM_TIME, SUM_TIME_SQ
        REAL TIME, TIME_Z0( 20 ), Z( MZTS, * ), Z0( * )
C
        AVG  = FLOAT( NAVG )
        DO I = 1, MZ
          Z0( I )    = 0.0
          TIME_Z0( I ) = 0.0
        ENDDO
        SUM_TIME    = 0.0
        SUM_TIME_SQ = 0.0
C
        DO J = 1, NAVG
          TIME        = DTT*FLOAT( J - 1 )
          SUM_TIME    = SUM_TIME + TIME
          SUM_TIME_SQ = SUM_TIME_SQ + TIME*TIME
          DO I = 1, MZ
            IF( IC_M( I ).NE.0 ) THEN
              Z0( I )    = Z0( I ) + Z( I, J )
              TIME_Z0( I ) = TIME_Z0( I ) + TIME*Z( I, J )
            ENDIF
          ENDDO
        ENDDO
        DEN = AVG*SUM_TIME_SQ - SUM_TIME*SUM_TIME
C
        DO I = 1, MZ
          IF( IC_M( I ).NE.0 ) THEN
            NUM    = AVG*TIME_Z0( I ) - Z0( I )*SUM_TIME
            Z0( I ) = ( Z0( I ) - SUM_TIME*NUM/DEN )/AVG
          ENDIF
        ENDDO
C
C Initial conditions for u,phi,theta,psi updated since data measured,
C but ICs for v,w estimated since they are unknown.
C
        IF( IC_M( 1 ).NE.0 ) THEN
          PARAM( 25 ) = ( Z0( 1 ) - PARAM( 13 ) )/( 1.0 + PARAM( 19 ) ) ! U0
        ENDIF
        IF( IC_M( 2 ).NE.0 ) THEN
          PARAM( 26 ) = ( Z0( 2 ) - PARAM( 14 ) )/( 1.0 + PARAM( 20 ) ) ! V0
        ENDIF
        IF( IC_M( 3 ).NE.0 ) THEN
          PARAM( 27 ) = ( Z0( 3 ) - PARAM( 15 ) )/( 1.0 + PARAM( 21 ) ) ! W0
        ENDIF
        IF( IC_M( 4 ).NE.0 ) THEN
          PARAM( 28 ) = ( Z0( 4 ) - PARAM( 16 ) )/( 1.0 + PARAM( 22 ) ) ! Theta0
        ENDIF
        IF( IC_M( 5 ).NE.0 ) THEN
```

```
          PARAM( 29 ) = ( Z0( 5 ) - PARAM( 17 ) )/( 1.0 + PARAM( 23 ) ) ! Phi0
        ENDIF
        IF( IC_M( 6 ).NE.0 ) THEN
          PARAM( 30 ) = ( Z0( 6 ) - PARAM( 18 ) )/( 1.0 + PARAM( 24 ) ) ! Psi0
        ENDIF
C
        if( ic_m( 7 ).ne.0 ) then
          param( 36 ) = ( z0( 7 ) - param( 39 ) )       ! X0
        endif
        if( ic_m( 8 ).ne.0 ) then
          param( 37 ) = ( z0( 8 ) - param( 40 ) )       ! Y0
        endif
        if( ic_m( 9 ).ne.0 ) then
          param( 38 ) = ( z0( 9 ) - param( 41 ) )       ! Z0
        endif
C
        RETURN
        END
C
*-----------------------------------------------------------------------------
*
        SUBROUTINE STATE_INIT( VAR, NK, PARAM, NSTS )
*
*       Subroutine to set initial conditions for state equations.
*
*       Modified by: M.L. Turner, SOG, ARL
*       Date: 16/5/'91
*
*-----------------------------------------------------------------------------
C
C       The following allows for either identification of initial conditions
C       or for updating based on identified bias and scale factor parameters
C
        REAL PARAM( * ), VAR( NSTS, * )
C
C       PARAM( 25 ) = ( Z0( 1 ) - PARAM( 13 ) )/( 1.0 + PARAM( 19 ) ) ! U0
C       PARAM( 26 ) = ( Z0( 2 ) - PARAM( 14 ) )/( 1.0 + PARAM( 20 ) ) ! V0
C       PARAM( 27 ) = ( Z0( 3 ) - PARAM( 15 ) )/( 1.0 + PARAM( 21 ) ) ! W0
C       PARAM( 28 ) = ( Z0( 4 ) - PARAM( 16 ) )/( 1.0 + PARAM( 22 ) ) ! Theta0
C       PARAM( 29 ) = ( Z0( 5 ) - PARAM( 17 ) )/( 1.0 + PARAM( 23 ) ) ! Phi0
C       PARAM( 30 ) = ( Z0( 6 ) - PARAM( 18 ) )/( 1.0 + PARAM( 24 ) ) ! Psi0
C
        VAR( 1, NK ) = PARAM( 25 )          ! Estimates u0
        VAR( 2, NK ) = PARAM( 26 )          ! Estimates v0
        VAR( 3, NK ) = PARAM( 27 )          ! Estimates w0
        VAR( 4, NK ) = PARAM( 28 )          ! Estimates phi0
        VAR( 5, NK ) = PARAM( 29 )          ! Estimates theta0
C       VAR( 6, NK ) = PARAM( 30 )          ! Estimates psi0
C
        VAR( 6, NK ) = 0.0         ! PSI0 = zero by definition
c
       var( 7, nk ) = 0.0               ! x0 = zero by definition
       var( 8, nk ) = 0.0               ! y0 = zero by definition
       var( 9, nk ) = param( 38 )       ! Estimates z0
C
        RETURN
        END
```

Resp.f

```
      SUBROUTINE RESP( AXRAW, AYRAW, P, Q, R, Y, NK, PARAM, UU,
     $     VAR, NSTS )
C
cAMA  Observations which are compared with Z (measurements) in 'HP1.Plot'
cAMA
cAMA  Modified Nov 90 to estimate centre of motion of ship and allow
cAMA  for pendulum attitude instruments.........................AMA
C
      REAL AXRAW, AYRAW, DelPhi, DelTht, PARAM( * ), P, Q, R
      REAL UU( * ), VAR( NSTS, * ), Y( * )
C
      DATA GRAV / 32.17405
C
C-------------------------------------------------
C     LIST Y(1),Y(2)...AS FUNCTIONS OF VAR(1), VAR(2)...,
C     PARAM(1), PARAM(2)... AND UU(1),UU(2)...
```

```
C-----------------------------------------------
C
C     VEL         = SQRT( VAR( 1, NK )**2 + VAR( 2, NK )**2
C     1         + VAR( 3, NK )**2 )
C
cAMA  Correct for accelerometer offset - PARAM(31,32,33) are x,y,z offsets
C
      P = ( 1.0 + PARAM( 10 ) )*UU( 4 ) + PARAM( 4 )
      Q = ( 1.0 + PARAM( 11 ) )*UU( 5 ) + PARAM( 5 )
      R = ( 1.0 + PARAM( 12 ) )*UU( 6 ) + PARAM( 6 )
      AxRaw       = uu( 1 ) + ( Q*Q + R*R )*PARAM( 31 )
     $     - ( P*Q )*PARAM( 32 ) - ( P*R )*PARAM( 33 )
     $     - GRAV*SIN( VAR( 5, NK ) )
      AyRaw       = uu( 2 ) - ( P*Q )*PARAM( 31 )
     $     + ( P*P + R*R )*PARAM( 32 ) - ( Q*R )*PARAM( 33 )
     $     + GRAV*COS( VAR( 5, NK ) )*SIN( VAR( 4, NK ) )
c
c     Correct for pendulum attitude instruments (pitch and roll)
c
      DelTht      = PARAM( 34 )*AxRaw
      DelPhi      = PARAM( 35 )*AyRaw
C
      Y( 1 )      = ( 1.0 + PARAM( 19 ) )*VAR( 1, NK ) + PARAM( 13 ) ! u (ship speed)
      Y( 2 )      = ( 1.0 + PARAM( 20 ) )*VAR( 2, NK ) + PARAM( 14 ) ! v
      Y( 3 )      = ( 1.0 + PARAM( 21 ) )*VAR( 3, NK ) + PARAM( 15 ) ! w
cAMA     Y( 4 )  = ( 1.0 + PARAM( 22 ) )*VAR( 4, NK ) + PARAM( 16 ) + DelPhi ! phi
cAMA     Y( 5 )  = ( 1.0 + PARAM( 23 ) )*VAR( 5, NK ) + PARAM( 17 ) + DelTht ! theta
      y( 4 ) = ( 1.0 + param( 22 ) )*var( 4, nk ) + param( 16 ) ! phi
      y( 5 ) = ( 1.0 + param( 23 ) )*var( 5, nk ) + param( 17 ) ! theta
      Y( 6 )      = ( 1.0 + PARAM( 24 ) )*VAR( 6, NK ) + PARAM( 18 ) ! psi
cAMA     y( 7 ) = var(7,nk) + param(39)     ! X
cAMA     y( 8 ) = var(8,nk) + param(40)     ! Y
      y( 7 ) = 0.0
      y( 8 ) = 0.0
      y( 9 ) = var(9,nk) + param(41)     ! Z
C
      RETURN
      END
```

APPENDIX C - MACTRANS '.BLK' FILES

Motion.Blk

```
L1
  12  11  10   8   7   9   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
0   0   0   0   0   0
L2
   2   3   4   6   5  51  52   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
0   0   0   0   0   0
```

Airwake.Blk

```
L1
  43  42  41  46  45  44  49  48   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
0   0   0   0   0   0
L2
  47  53  54  31  32  16  17  18   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
0   0   0   0   0   0
L3
  19   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
0   0   0   0   0   0
```

APPENDIX D - STATISTICS FOR 135° 10 KN RELATIVE WIND

Wind 135°, 10 kn
Position 1
20091337

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	11.96	11.24	-2.23	-1.58	-2.57	-1.10	-0.76	-1.43	-0.54	-0.25	0.60	-3.28	-3.66
Maximum	12.19	12.72	1.54	1.47	3.38	0.63	1.47	1.83	0.53	0.35	1063.70	8.31	2.44
Mean	12.04	12.04	0.00	-0.06	0.36	-0.32	0.30	-0.02	0.00	0.00	532.15	3.84	0.00
Std Deviation	0.03	0.32	0.74	0.76	1.40	0.33	0.56	0.77	0.21	0.14	307.87	3.17	1.59

Wind 135°, 10 kn
Position 2
20091340

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	11.87	11.49	-1.54	-1.95	-2.61	-0.87	-0.66	-1.85	-0.38	-0.38	0.60	-6.96	-2.64
Maximum	12.13	12.47	1.53	1.33	3.21	0.27	0.84	1.77	0.42	0.28	1213.30	4.30	2.45
Mean	11.97	11.97	0.00	-0.03	0.45	-0.31	-0.14	-0.01	0.00	-0.01	606.48	-1.68	0.01
Std Deviation	0.04	0.20	0.64	0.67	1.20	0.22	0.31	0.68	0.17	0.12	349.26	2.09	1.16

Wind 135°, 10 kn
Position 3
20091343

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	11.87	11.12	-3.99	-2.15	-4.75	-1.30	-0.81	-3.00	-0.68	-0.40	0.59	-24.98	-3.69
Maximum	12.15	12.72	2.67	1.52	3.77	0.87	1.00	2.48	0.69	0.55	1045.40	27.00	4.00
Mean	11.96	11.96	0.01	-0.09	0.32	-0.31	0.20	0.03	0.01	0.00	523.91	1.75	0.00
Std Deviation	0.05	0.37	1.59	0.85	1.74	0.41	0.41	1.05	0.28	0.17	302.70	18.52	1.73

Wind 135°, 10 kn
Position 4
20091347

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	11.87	11.25	-4.68	-1.85	-4.47	-1.08	-0.70	-2.71	-0.53	-0.32	0.57	-33.55	-3.10
Maximum	12.15	12.59	3.08	2.34	4.57	0.46	0.97	2.83	0.57	0.45	1415.30	33.36	4.67
Mean	11.95	11.95	0.00	-0.12	0.51	-0.32	0.14	0.00	0.00	0.01	707.13	1.34	0.00
Std Deviation	0.03	0.34	1.44	0.89	1.57	0.31	0.37	0.96	0.19	0.15	408.58	22.55	1.64

Wind 135°, 10 kn
Position 5
20091350

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	11.91	11.34	-1.97	-1.90	-3.38	-1.00	-1.21	-2.38	-0.56	-0.37	0.64	-19.21	-4.56
Maximum	12.16	12.96	3.28	2.10	4.28	0.77	0.24	2.37	0.58	0.36	1040.90	14.77	3.00
Mean	12.03	12.03	0.01	-0.01	0.49	-0.24	-0.47	0.00	-0.01	-0.01	521.07	-2.75	0.00
Std Deviation	0.03	0.41	1.16	0.85	1.70	0.41	0.40	0.99	0.25	0.15	299.79	11.63	1.72

Wind 135°, 10 kn
Position 6
20091330

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	12.00	11.43	-1.74	-1.43	-1.85	-0.97	-0.51	-1.20	-0.52	-0.33	0.60	-11.17	-2.67
Maximum	12.17	12.60	2.15	1.61	2.79	0.35	0.73	1.05	0.52	0.21	1051.40	12.35	3.91
Mean	12.04	12.04	0.00	-0.06	0.20	-0.31	0.15	0.00	0.00	0.00	525.98	1.51	0.00
Std Deviation	0.02	0.31	0.86	0.78	1.13	0.29	0.33	0.57	0.18	0.12	302.58	7.57	1.47

Wind 135^{o}, 10 kn
Position 7
20091334

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	11.99	11.25	-2.27	-1.45	-2.90	-0.86	-1.03	-1.96	-0.36	-0.28	0.61	-11.59	-2.76
Maximum	12.19	12.68	1.69	1.36	2.91	0.36	0.35	2.09	0.42	0.33	1026.70	4.92	3.24
Mean	12.03	12.03	0.01	-0.05	0.34	-0.31	-0.39	0.01	-0.01	0.00	513.64	-3.16	0.00
Std Deviation	0.02	0.31	0.80	0.68	1.09	0.29	0.31	0.67	0.18	0.13	297.86	4.96	1.31

Wind 135^{o}, 10 kn
Position 8
20091307

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	9.88	9.54	-4.18	-1.30	-1.93	-1.04	-0.68	-1.76	-0.44	-0.26	0.50	-21.96	-2.10
Maximum	10.09	10.52	2.47	1.56	3.90	0.35	0.65	1.51	0.48	0.30	581.49	22.40	2.93
Mean	9.95	9.95	0.02	-0.12	0.66	-0.32	0.05	-0.03	-0.02	0.00	291.44	0.37	0.00
Std Deviation	0.04	0.26	1.72	0.65	1.49	0.32	0.34	0.90	0.21	0.13	167.95	14.67	1.30

Wind 135^{o}, 10 kn
Position 9
20091311

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	9.60	9.16	-3.02	-1.26	-3.48	-1.09	0.00	-2.10	-0.49	-0.24	0.48	-3.04	-3.59
Maximum	9.89	10.40	2.34	1.51	3.58	0.44	2.31	2.28	0.67	0.28	945.51	22.23	2.29
Mean	9.70	9.70	0.04	-0.07	0.06	-0.32	1.18	0.00	0.00	0.01	473.78	9.34	0.00
Std Deviation	0.06	0.29	1.12	0.70	1.64	0.33	0.58	0.96	0.22	0.11	271.83	7.71	1.39

Wind 135^{o}, 10 kn
Position 10
20091315

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	9.70	9.26	-2.28	-1.59	-2.47	-1.12	-1.35	-2.10	-0.54	-0.41	0.50	-15.87	-2.73
Maximum	9.94	10.36	2.07	1.55	3.85	0.24	0.49	2.19	0.43	0.45	962.95	7.73	3.14
Mean	9.79	9.79	-0.01	-0.07	0.37	-0.32	-0.59	0.02	0.00	0.00	482.62	-4.23	0.00
Std Deviation	0.04	0.22	0.86	0.58	1.38	0.27	0.41	0.88	0.19	0.15	278.26	7.97	1.17

Wind 135^{o}, 10 kn
Position 11
20091326

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	10.20	9.67	-3.04	-1.72	-3.47	-0.95	-0.28	-1.87	-0.54	-0.22	0.50	-22.13	-2.71
Maximum	11.47	11.84	4.62	1.35	3.08	0.61	1.64	2.21	0.52	0.39	935.59	33.53	3.13
Mean	10.82	10.82	0.03	-0.04	0.05	-0.30	1.00	-0.01	-0.01	0.02	458.86	6.86	0.00
Std Deviation	0.38	0.48	1.85	0.76	1.59	0.29	0.38	0.92	0.19	0.11	270.62	18.64	1.48

Wind 135^{o}, 10 kn
Position 12
20091323

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	9.49	8.88	-1.09	-1.73	-2.61	-1.25	-1.10	-1.70	-0.45	-0.28	0.48	-13.19	-2.96
Maximum	9.90	10.53	1.16	1.16	2.73	0.45	0.04	1.66	0.63	0.31	876.42	4.62	2.61
Mean	9.70	9.70	0.00	-0.03	0.23	-0.33	-0.61	0.01	0.00	0.00	436.53	-4.57	0.00
Std Deviation	0.08	0.38	0.52	0.59	1.29	0.36	0.25	0.79	0.22	0.12	254.50	5.93	1.28

Wind 135^{o}, 10 kn
Position 13
20091319

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	9.56	9.10	-2.15	-1.73	-2.88	-1.23	-1.90	-2.28	-0.69	-0.29	0.49	-11.62	-2.38
Maximum	9.88	10.13	1.95	1.42	3.71	0.57	0.91	2.11	0.69	0.33	884.46	7.96	3.27
Mean	9.67	9.67	0.01	-0.09	0.51	-0.31	-0.41	-0.01	0.00	0.01	442.84	-0.53	0.02
Std Deviation	0.05	0.26	0.85	0.60	1.55	0.38	0.81	0.99	0.28	0.14	254.16	5.97	1.09

APPENDIX E - SELECTED SHIP MOTION STATISTICS

Ship Stationary
Position 8
16091506

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	0.05	-0.35	-0.47	-0.55	0.18	-0.67	0.00	-0.05	-0.03	-0.02	-0.05	-1.50	-1.44
Maximum	0.05	0.51	0.54	0.57	0.36	-0.55	0.14	0.05	0.03	0.02	4.69	1.92	1.62
Mean	0.05	0.05	0.00	-0.02	0.27	-0.61	0.09	0.00	0.00	0.00	1.81	-0.01	0.00
Std Deviation	0.00	0.22	0.21	0.28	0.05	0.03	0.03	0.03	0.02	0.01	1.18	1.14	0.66

Wind 00^{o}, 10 kn
Position 10
19091053

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	31.04	29.91	-1.64	-2.91	-1.86	-1.38	-0.97	-0.91	-0.55	-0.48	1.58	-3.64	-5.73
Maximum	31.47	32.27	2.25	1.08	1.27	0.09	1.53	0.85	0.58	0.44	2764.70	32.43	6.21
Mean	31.29	31.29	0.00	-0.30	-0.61	-0.55	0.65	0.01	0.00	0.00	1386.55	14.17	0.00
Std Deviation	0.14	0.53	0.82	0.83	0.76	0.34	0.57	0.31	0.23	0.19	797.22	12.24	3.04

Wind 00^{o}, 20 kn
Position 8
19091624

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	12.82	11.20	-2.20	-1.87	-0.39	-1.57	-0.36	-1.04	-1.13	-0.26	0.63	-16.05	-11.22
Maximum	13.26	14.04	2.54	2.15	2.43	0.52	0.85	1.14	0.93	0.30	1208.40	25.11	15.18
Mean	12.95	12.95	0.01	0.03	1.14	-0.46	0.13	0.01	0.00	0.00	604.49	2.81	-0.01
Std Deviation	0.04	0.88	1.18	1.01	0.61	0.38	0.32	0.46	0.36	0.12	342.39	12.79	7.73

Wind 00^{o}, 35 kn
Position 5
19091714

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	36.80	36.07	-1.99	-2.61	-1.63	-1.55	-0.51	-0.62	-1.06	-0.32	1.80	-5.30	-4.77
Maximum	38.70	39.30	1.59	1.35	0.44	0.51	1.13	0.68	1.11	0.31	2170.30	19.77	5.93
Mean	37.82	37.82	-0.01	-0.24	-0.81	-0.45	0.42	0.00	0.02	0.01	1077.44	7.21	-0.01
Std Deviation	0.54	0.75	0.94	0.93	0.46	0.45	0.46	0.26	0.47	0.13	625.21	7.99	2.64

Wind 30^{o}, 10 kn
Position 8
20091424

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	41.10	39.51	-3.02	-2.22	-2.73	-1.05	-0.45	-0.76	-0.41	-0.37	2.06	-10.07	-3.74
Maximum	41.50	42.50	3.20	1.60	1.35	0.24	3.29	0.64	0.37	0.45	3522.00	99.85	4.88
Mean	41.28	41.27	-0.01	-0.24	-0.71	-0.28	1.63	-0.02	0.00	0.03	1763.09	53.24	0.00
Std Deviation	0.16	0.75	1.53	0.89	1.12	0.31	1.08	0.35	0.14	0.20	1011.83	39.09	1.95

Wind 30^{o}, 20 kn
Position 10
18091428

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	24.04	23.20	-1.22	-1.65	-1.25	-1.45	-0.69	-0.45	-0.82	-0.26	1.23	0.03	-2.41
Maximum	24.05	24.54	1.05	0.95	0.09	0.09	1.02	0.57	0.76	0.23	2172.10	12.22	2.59
Mean	24.04	24.04	0.00	-0.29	-0.53	-0.66	0.16	-0.01	-0.01	0.00	1086.65	5.35	-0.01
Std Deviation	0.00	0.27	0.41	0.44	0.28	0.28	0.44	0.20	0.31	0.09	627.25	3.96	0.89

Wind 30°, 35 kn
Position 8
21091243

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	28.59	27.95	-1.98	-1.35	-3.24	-1.25	-0.60	-0.65	-0.26	-0.30	1.47	-4.14	-2.28
Maximum	30.09	30.91	1.29	1.02	-0.87	-0.06	1.93	0.40	0.33	0.49	2692.80	26.38	2.94
Mean	29.47	29.46	0.02	-0.31	-1.95	-0.59	0.47	0.00	0.00	0.01	1336.14	6.34	0.00
Std Deviation	0.42	0.70	0.64	0.49	0.50	0.27	0.67	0.19	0.12	0.15	779.62	10.72	1.14

Wind 60°, 10 kn
Position 10
18091529

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	16.43	15.66	-1.12	-1.34	-1.59	-1.27	-0.83	-1.03	-0.66	-0.20	0.83	-6.51	-3.28
Maximum	16.61	17.13	1.19	1.41	1.56	-0.12	0.91	0.95	0.50	0.23	1646.90	4.91	2.51
Mean	16.47	16.48	0.00	-0.19	-0.03	-0.65	0.15	0.00	0.00	0.00	823.55	-0.79	-0.01
Std Deviation	0.02	0.39	0.43	0.59	0.69	0.25	0.44	0.41	0.22	0.10	474.44	3.52	1.26

Wind 60°, 20 kn
Position 10
20091158

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	18.54	17.80	-1.45	-2.29	-2.52	-1.53	-1.03	-1.33	-1.19	-0.33	0.96	-19.41	-3.63
Maximum	18.74	19.63	1.64	1.53	1.35	0.66	0.49	1.42	0.88	0.37	1663.00	10.99	2.86
Mean	18.60	18.60	0.00	-0.14	-0.82	-0.33	-0.36	-0.01	0.00	-0.01	832.31	-5.07	0.00
Std Deviation	0.03	0.42	0.74	0.70	0.78	0.43	0.36	0.52	0.39	0.14	478.36	10.15	1.39

Wind 90°, 10 kn
Position 8
18091626

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	9.37	8.76	-1.20	-1.81	-1.46	-1.15	-0.41	-1.19	-0.44	-0.26	0.47	-4.91	-2.65
Maximum	9.51	10.13	1.14	1.04	2.17	-0.05	0.70	1.26	0.54	0.21	942.27	5.44	2.70
Mean	9.43	9.43	-0.03	-0.12	0.44	-0.63	0.10	0.00	0.00	0.01	472.19	-0.18	-0.15
Std Deviation	0.03	0.34	0.48	0.55	0.71	0.19	0.29	0.49	0.17	0.09	271.53	2.68	1.54

Wind 90°, 20 kn
Position 11
21091424

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	7.73	7.11	-1.54	-1.23	-2.32	-0.97	-0.18	-1.37	-1.06	-0.34	0.41	-4.23	-3.40
Maximum	7.89	8.37	1.52	1.82	2.29	0.67	0.87	1.09	0.52	0.27	462.63	14.69	4.35
Mean	7.80	7.79	0.06	0.09	-0.12	-0.29	0.30	0.01	-0.02	0.01	231.43	4.59	0.62
Std Deviation	0.02	0.28	0.69	0.64	1.20	0.34	0.27	0.63	0.29	0.12	133.54	6.39	1.30

Wind 180°, 10 kn
Position 6
20090930

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	5.17	3.61	-1.33	-2.15	-2.24	-1.28	0.00	-2.08	-0.52	-0.31	0.24	-8.09	-8.22
Maximum	5.34	6.81	1.60	2.09	3.79	0.28	2.60	1.52	0.51	0.23	438.18	13.83	11.83
Mean	5.25	5.25	0.00	-0.05	1.01	-0.46	1.26	-0.02	0.00	0.03	219.51	3.13	-0.02
Std Deviation	0.03	0.83	0.77	1.01	1.37	0.36	0.77	0.81	0.20	0.11	124.50	6.62	5.92

Wind 180^{o}, 10 kn
Position 8
20090956

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	7.77	6.89	-1.94	-1.90	-4.97	-1.21	-0.59	-3.21	-0.45	-0.29	0.47	-18.18	-9.95
Maximum	7.90	9.38	3.17	2.59	5.26	0.44	0.91	2.99	0.45	0.31	683.14	7.85	18.18
Mean	7.82	7.82	-0.01	0.25	0.24	-0.44	0.12	-0.02	0.00	0.01	341.83	-0.74	0.05
Std Deviation	0.02	0.55	1.10	1.04	2.09	0.37	0.35	1.25	0.19	0.11	193.34	8.15	5.69

Wind 180^{o}, 10 kn
Position 9
20091000

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	7.60	6.06	-2.93	-1.94	-4.04	-1.40	-1.60	-2.60	-0.51	-0.43	0.47	-22.57	-16.34
Maximum	7.72	9.39	3.16	2.98	5.08	0.35	1.15	2.96	0.55	0.45	647.02	27.14	9.40
Mean	7.66	7.66	-0.01	0.20	0.26	-0.40	-0.13	0.02	-0.01	-0.02	323.62	0.79	0.00
Std Deviation	0.01	0.69	1.48	0.94	1.65	0.42	0.73	0.99	0.25	0.17	187.07	17.96	5.15

Wind 180^{o}, 10 kn
Position 13
20090920

Statistics	U_m (ft/s)	U (ft/s)	V (ft/s)	W (ft/s)	ϕ (deg)	θ (deg)	ψ (deg)	p (deg/s)	q (deg/s)	r (deg/s)	X (ft)	Y (ft)	Z (ft)
Minimum	7.63	6.72	-1.61	-1.86	-2.64	-1.00	-0.18	-2.37	-0.43	-0.21	0.46	-4.62	-14.57
Maximum	7.87	9.30	1.16	2.32	5.09	0.13	1.42	2.31	0.45	0.27	636.77	6.50	8.42
Mean	7.74	7.73	0.01	0.22	1.25	-0.45	0.49	-0.04	0.00	0.02	317.38	2.36	-0.03
Std Deviation	0.06	0.57	0.60	0.88	1.74	0.22	0.41	1.04	0.17	0.10	182.13	2.95	4.67

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Part II - Removal of Ship Motion Effects from Measured Airwake Data
A. M. Arney

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A trial to measure ship motion and airwake has been carried out aboard an 'Adelaide' class FFG-7 frigate. This document outlines a process that has been developed whereby the ship attitudes, velocities, and displacement, including initial conditions, may be determined from limited measured data. The use of software developed to remove the resulting ship motion from the measured airwake data is also shown.

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